Effectiveness of Virtual Teaching Assistant Software for Circuits Open Laboratory

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***Abstract*—In this paper, a Virtual Open Laboratory Teaching Assistant (VOLTA) has been developed, which provides the students a self-paced open laboratory environment with virtual teaching assistance in an undergraduate circuits laboratory. This web-based software assists the students in performing the circuits laboratory at the students' convenience even when the teaching assistant is not present. This way, VOLTA increases the laboratory guidance for the students, while reducing the workload of human teaching assistants. The advantages of VOLTA include individual, self-paced learning, 24/7 accessibility, personalized instructions for shy students, increased levels of engagement, and efficient use of limited resources (e.g. space, lab equipment, teaching assistant etc.). In this study, the effectiveness of VOLTA and the traditional laboratory was compared for an undergraduate circuit course. The results show that: 1) the students found VOLTA to be satisfactory, and 2) the students participating in VOLTA performed better on quizzes. The analysis of variance (ANOVA) test was performed on the gain scores derived from the pre-tests/post-tests of the traditional and VOLTA students. The null hypothesis is that there is no difference among the gain scores of the students from the control (traditional) and experimental (VOLTA) groups. The ANOVA test showed $p < 0.001$, which indicates VOLTA significantly improved the student performance on the test. This study suggests that VOLTA can be used as an effective teaching tool in circuits laboratories.**

***Index Terms*—Electrical engineering education, virtual teaching assistant, open laboratory, circuits laboratories.**

I. Introduction

LABORATORIES are a quintessential part of the engineering education in order to deliver the hands-on experience of engineering concepts to students. Traditional on-site circuit laboratories have several drawbacks, such as teaching assistance guidance, limited space, schedule conflicts and short term exposure. Over the past decades, educators have been exploring virtual laboratories to mitigate these issues [1], [2]. Different approaches have been attempted in different branches of engineering such as controls [3], process engineering [4], nanotechnology [5], chemical engineering [6], robotics [7], virtual laboratories [8], and remote laboratories [9]. These methods, however, do not replace the traditional "closed laboratory" environment.

In a traditional "closed laboratory" environment, students perform the assignments following a 'cookbook' lab manual and submit a written report drafted after the laboratory has been completed. Knight and DeWeerth argued that this format is not the most conducive to learning [10]. Space constraints are mitigated by dividing the students into multiple sections. Sometimes, scheduling constraints force a lab to be performed out of sequence with the lecture. Because of time constraints, students receive a less-than-ideal exposure to the concepts and the associated instrumentation.

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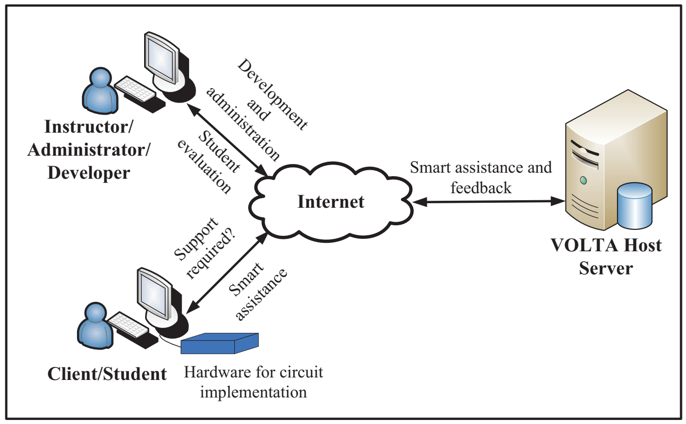

Fig. 1: Physical architecture of VOLTA.

Open laboratory is one of the new, promising approaches in engineering education. An open laboratory is where the students can return to repeat and refine their experiments. Palais and Javurek defined the open laboratory as "a single large room containing equipment for performing experiments associated with all the electrical engineering undergraduate laboratories" [11]. The motivation of the open laboratory lies in its ability to maximize resource utilization. Lab scheduling becomes more flexible, and the equipment is more effectively utilized [12], [13]. However, the open laboratory requires self-paced labs that can be completed without direct supervision.

In a traditional laboratory approach, teaching assistants (TAs) help the students with assembly and debugging. Students can also receive help individually from TAs during office hours. For a large number of students with a limited number of TAs, delivering on-demand help becomes very difficult. The goal of this paper is to transform traditional laboratories to open laboratories for basic electrical engineering courses such as Circuits. In order to mitigate the availability issue of teaching staff, an intelligent system has been proposed that can provide "virtual teaching assistance" to the students. This system is called the "Virtual Open Laboratory Teaching Assistant". Previously, Butz *et al.* developed a universal virtual laboratory to assist individuals who do not have adequate mobility of their upper bodies to perform laboratory experiments [14]. For that framework, they discussed circuit element recognition in a virtual laboratory [15]. Also, they described natural language recognition in an intelligent tutor system [16]. VOLTA has been motivated by these approaches adopted in the universal virtual laboratory.

Equipped with pre-lab testing and instruction, engineering design exercises, short topic explanation videos, instrumentation instruction (including safety), and a corresponding post-lab test module, VOLTA is able to provide on-demand, and smart assistance to the students. In the preliminary study, the students participating in VOLTA performed slightly better compared to traditional laboratory students in Fall 2014 [17]. In that experiment, the ANOVA test was run on the gain score of the students. The gain score is the difference between the post- and pre-test score. It has been found that the VOLTA students did well compared to the traditional students with a p-value of 0.117 [17]. In Spring 2015, VOLTA was revamped and another experiment was performed. A "Hardware Help" feature was added for the students to troubleshoot their circuits. In this paper, VOLTA software design is described. Then, the use of VOLTA in a circuit course is shown. After that, an assessment of VOLTA's application in an entry-level circuit course is presented. The analysis shows that VOLTA significantly increases learning in circuits laboratories.

The rest of the paper is organized as follows: Sections II and III describe the overview of VOLTA design and implementation. Section IV discusses the evaluation methods used to assess the effectiveness of VOLTA. Results are presented in Section V. Finally, discussion and conclusion are presented.

II. VOLTA Design

In this section, the physical architecture and different modules in VOLTA software are discussed. The detailed description can be found in [17].

A. System Architecture

VOLTA is a system which can guide a student to perform hardware electrical engineering circuits laboratory without any human teaching assistant. Fig. 1 shows the physical architecture of VOLTA. The different modules of VOLTA, hosted in a server, are accessible via internet for the instructors, developers, and students. The students have portable and compact circuit hardware for the lab. VOLTA is preloaded with instructional videos, definitions, and explanations. It supports on-demand learning and provides immediate feedback on laboratory exercises and quizzes. For instructors, it provides an administration panel that supports management of the laboratory content.

B. Software Modules

VOLTA software consists of five modules and a database. The modules are (1) Instructor module, (2) Student module, (3) Help module, (4) Circuit Recognizer module, and (5) Speech module.

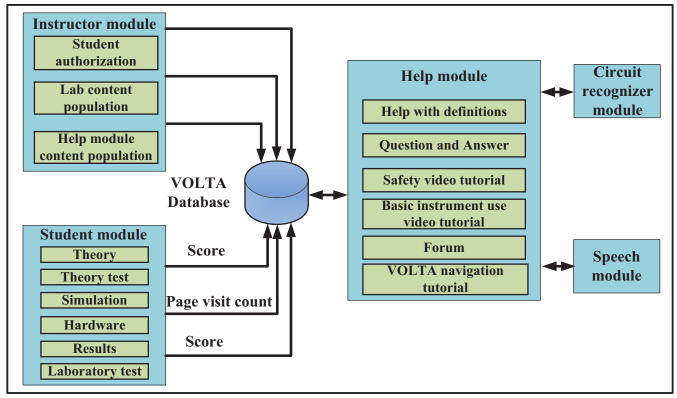

Fig. 2: VOLTA software modules.

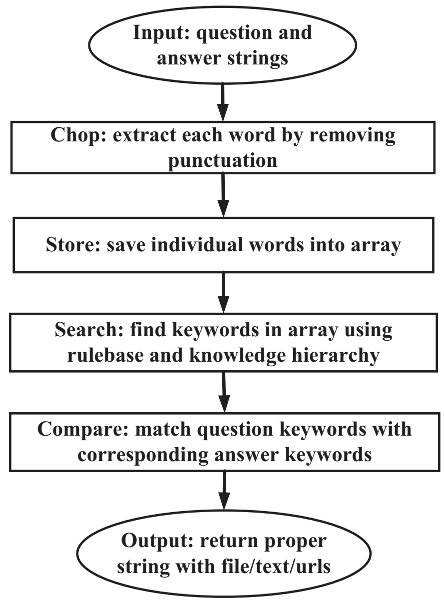

Fig. 3: Question and answer query flowchart.

1) Instructor module: The Instructor module provides a flexible environment for an instructor or teaching assistant to perform his/her tasks. It authorizes the students for access in VOLTA through the student module. The instructor can update the lab contents via an administration panel. It also helps upload the supporting materials into the database for the Help module.

2) Student module: The Student module is the part of VOLTA that interacts with the students. It guides the students step-by-step for completing an experiment. It helps the student to understand the subject clearly through tests. It evaluates the student before and after the labwork.

3) Help module: This module provides the students with teaching assistance in virtual format. The students can seek help from this module at any point of VOLTA session. This module provides multiple sub-modules consisting of definitions of circuit terminology, questions and answers about basic circuit and the related lab. A search algorithm was deployed in VOLTA for finding the appropriate answers to the students' query. The flowchart is shown in Fig. 3. There are also safety video tutorials, basic instrument use video tutorials, forum for discussing the problems, and how-to-use VOLTA video

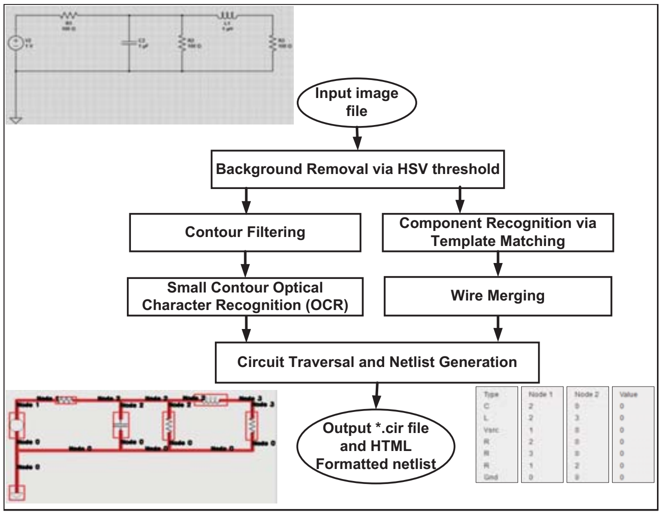

Fig. 4: Flowchart of Circuit Recognition Algorithm.

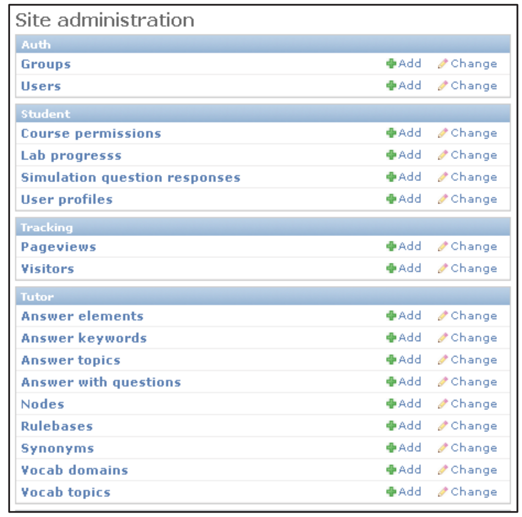

Fig. 5: VOLTA administration panel for instructors.

tutorial. These sub-modules are pre-loaded with the necessary materials by the instructor. It works in conjunction with a circuit recognizer module and a speech module. The Circuit Recognizer helps the students verify and debug their circuits.

4) Circuit Recognizer module: The Circuit Recognizer helps the students verify their simulated circuits and debug their hardware circuits. This module contains an image processing algorithm for automatic recognition of the circuit schematics. Fig. 4 shows the flowchart for the circuit recognition process. The students upload their schematic for simulation in VOLTA. The schematic serves as the input to the module. The image processing performs background removal, contour filtering, and component recognition via template matching [18], [19]. Finally, the module outputs a schematic with labeled nodes, components with values, and an HTML formatted netlist (word description of the circuit). This module also helps debug a hardware circuit by providing troubleshooting steps. A hardware circuit may not work properly for a few reasons, such as bad connections, bad components, incorrect wiring, bad instrument setting, and power problems. With hardware help, VOLTA can help students like a teaching assistant.

5) Speech Module: The Speech module provides a more flexible means for assisting the student. This module can offer help by detecting the emotional state of the student. The speech module records the students' voices, which will be analyzed for emotional state detection. Then VOLTA can offer help to the students.

III. VOLTA Implementation

VOLTA software is implemented using Python (version 2.7.1) and Django (version 1.6.5). Django is a high-level Python web framework for rapid and scalable web development [20]. This framework is divided into three layers: model layer, view layer, and template layer. The model layer is an abstraction layer provided by Django for structuring and manipulating the data of the web application. For VOLTA, the SQlite database engine was used. The views layer is used to encapsulate the logic responsible for processing a user's request and for returning the response. In other words, it determines the URLs (Universal Resource Locator) or the web addresses, and then returns the user with the response (web page). The template layer offers a syntax for rendering the information to be presented to the user. This means that the designer can create certain HTML (HyperText Markup Language) templates with static parts and syntax facilitating the dynamic content insertion. In this way, for each user a dynamic HTML page is generated.

Fig. 5 shows the administration panel of VOLTA. Through this administration panel, the metadata of the model can be read and the content can be added. The database of VOLTA can be loaded with content in two ways: via python scripts and via admin panel. Practically, before making the website live, it is convenient to load the content using scripts. After making the website live, the admin panel is used for adding contents. In this way, overwriting the current user information can be avoided. Fig. 5 shows the options for creating and authorizing users, adding different lab elements, and monitoring the lab progress of the student.

The VOLTA user interface guides students through an experiment step-by-step as shown in Fig. 6. The students take part in pre-tests and post-tests that consist of multiple choice questions. The same set of questions are asked in pre- and post-tests. In post-tests, the multiple choice options are not in the same order as in pre-tests. After the pre-test, the students are directed to the simulation section. In this section, the students are instructed to simulate their circuits before constructing a hardware implementation. The hardware section provides instructions for building circuit in the breadboard.

The student uses a Digilent EE (Electronics Explorer) board (Digilent Inc., Pullman, Washington, USA) for hardware implementation [21]. The EE board is built around a solderless breadboard, which also includes oscilloscopes, waveform generators, power supplies, voltmeters, reference voltage generators, and thirty-two digital signals that can be configured as a logic analyzer, pattern generator, or any one of several static digital I/O devices (Fig. 7). All of these instruments can be connected to circuits built on the solderless breadboards using simple jumper wires. For data acquisition and analysis, the PC-based software named "WaveForms" is

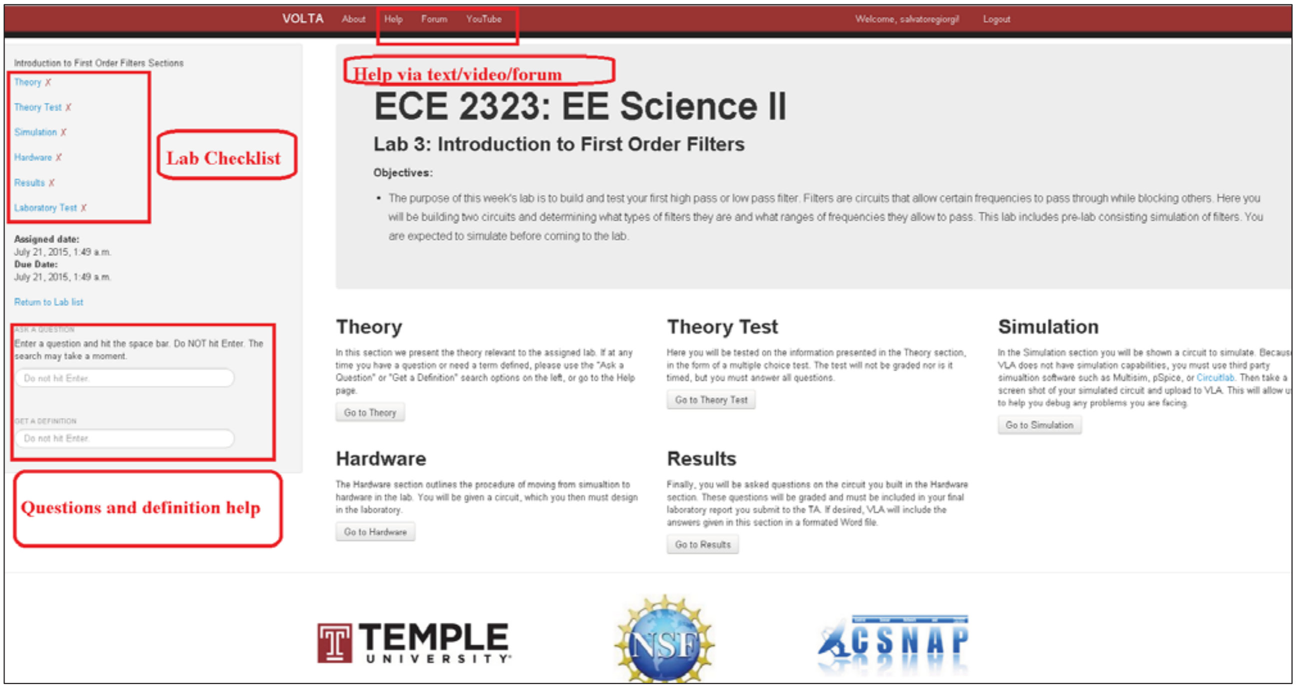

Fig. 6: User interface for the students.

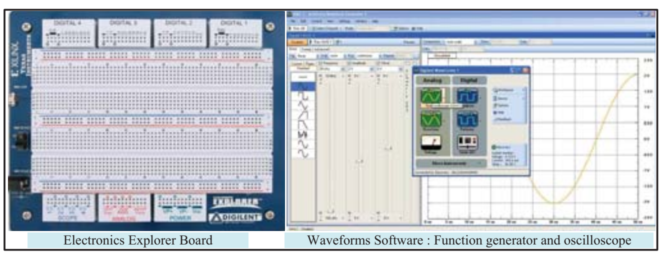

Fig. 7: Electronic Explorer board from Digilent and the Waveforms software.

used. A high-speed USB 2.0 connection ensures near real time data acquisition.

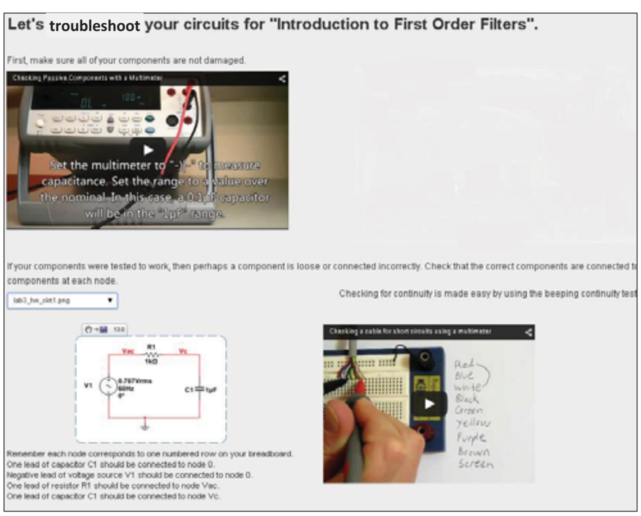

Fig. 8: Circuit tracer in VOLTA.

In the Hardware section, VOLTA provides a feature called 'circuit tracer' for tracing circuit connections. The troubleshooting guide starts with the component integrity test. A video tutorial is provided to check whether the components are damaged. Secondly, another video tutorial shows how to do the continuity test to check whether there is any loose connection. A brief description of circuit node and component connectivity is given for the desired circuit. This description is generated from a previously-loaded netlist of the circuit. Fig. 8 shows the Hardware Help interface.

The Results section contains the guideline for the contents of report. At the end of the lab, the students take a Laboratory Test which is in multiple-choice format.

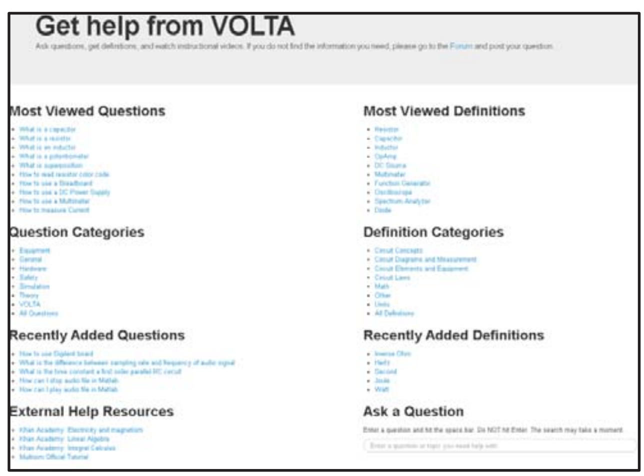

Fig. 9: Help module implementation.

Fig. 9 shows the help page of VOLTA. The students can look for questions, answers, and definitions. This page gives a summary list of the most viewed questions and definitions.

Also, there are video tutorials for performing basic circuit laboratory work. Fig. 10 shows the prerequisite material page with video instructions for doing labwork.

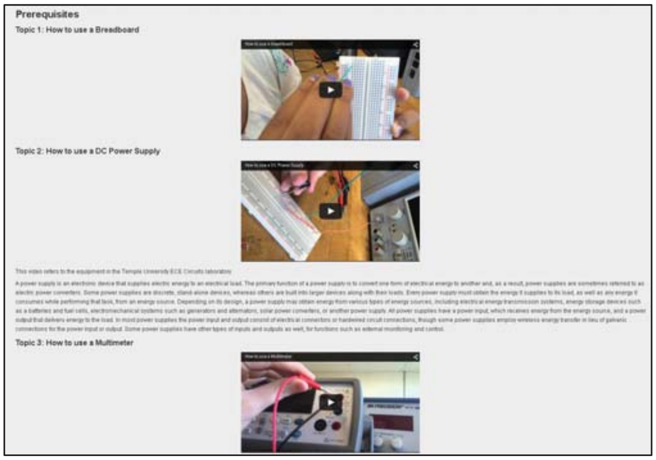

Fig. 10: Instructional videos in help module.

IV. Evaluation of VOLTA

VOLTA was evaluated from two perspectives: usability and effectiveness. Usability evaluation data provides knowledge about a program's functional effectiveness, efficiency, ease of learning, ease of use, motivational influence, and quality assurance. The effectiveness study of VOLTA provides insights about its usefulness compared to traditionally taught classes. The IRB approval was obtained from Temple University (Protocol number is 22447).

A. Usability Evaluation

A Likert scale for usability evaluation was used for the usability evaluation. The Likert scale is the most widely used technique to measure attitude. It evaluates the attitude toward a topic by presenting a set of statements about topic to the respondents [22]. The respondents are asked to indicate whether they strongly agree, agree, disagree, strongly disagree, or hold no opinion about the statements. Their responses are assigned numeric values, e.g. strongly disagree = 1, disagree = 2, no opinion = 3, agree = 4 and strongly agree = 5. The mean attitude score can be calculated then by averaging their response scores according to Likert scale [22, p. 210]. The mean score below 3 shows the negative attitude and above 3 shows the positive attitude.

In this study, twenty questions were asked covering seven broad categories:

A. Did the students think VOLTA was useful for their learning? (Learning environment)
B. Did the students find the software motivating? (Motivational value)
C. Did the students find VOLTA easy to use? (Ease of use)
D. Did the students perceive the usefulness of various features of VOLTA? (Perception of usefulness)
E. Did the students trust the virtual laboratory environment? (Authenticity of virtual learning)
F. What was the perceived quality of VOLTA? (Quality assurance)
G. What additional features the students would like to see in VOLTA? (Expectations)

B. Effectiveness Assessment

The study involved the students enrolled in a course on circuits. The course had two sections. The students were randomly assigned to each section. The sections were randomly chosen as experimental and control groups. The students in the experimental group received a curriculum in which the instructor integrated VOLTA. The students in the control group received the traditional course curriculum. The effectiveness of VOLTA is assessed using gain score analysis of pre-test/post-test design [23].

Eleven lab assignments were developed for use with VOLTA. With each lab assignment, there was one pre- and post-test. The lab assignments were as follows:

- Lab 1 Introduction to Multisim using RC Circuit.
- Lab 2 Introduction to Digilent Board using RC Circuit.
- Lab 3 Introduction to First Order Filters.
- Lab 4 Step Response of a Second Order Filter.
- Lab 5 Frequency Response of a Second Order Filter.
- Lab 6 Second Order Circuit Design Based on Step Response.
- Lab 7 Impedance Measurement of AC Circuit.
- Lab 8 Bass Booster Implementation using Active Filters.
- Lab 9 Gain Bandwidth Product and Slew Rate of Op-amp.
- Lab 10 Introduction to Boost Converter.
- Lab 11 Introduction to Amplitude Modulation.

V. Results

A. Usability

The usability evaluation is based on the data that were collected through a student survey. During Spring 2015, the usability data collection a survey questionnaire was sent to ten students. These students were enrolled in an introductory AC circuit lab "EE Science II". They volunteered to use VOLTA. Seven out of ten students completed the survey questionnaire. Fig. 11 shows the mean attitude scores of seven individuals. All of them except one showed positive attitude towards VOLTA. Fig. 12 shows category-wise mean attitude score. In all seven categories, the students showed positive attitude.

In category A, five Likert-type questions were asked to understand how successful VOLTA was as a learning environment. At least 57% of the responses agreed that they viewed VOLTA as a useful learning tool. In category B, two questions were asked to assess the motivational value of VOLTA. At least 43% of the students agreed that they enjoyed using VOLTA. In category C, three questions were asked regarding the ease of use of VOLTA. 99% of the students found VOLTA easy to use and easy to navigate. The students also felt that the use of VOLTA was intuitive (85%). In category D, four questions were asked regarding to what degree VOLTAs features were helpful. 71% of the

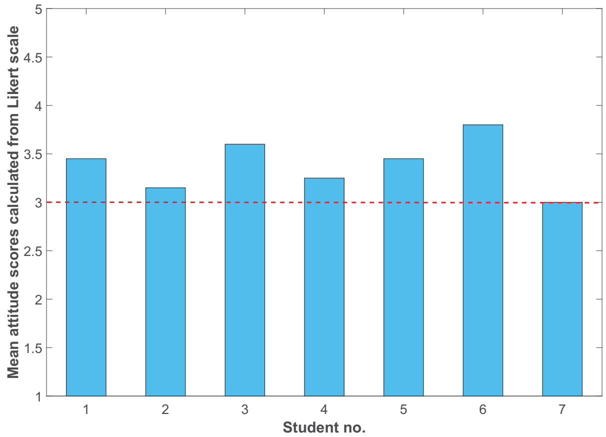

Fig. 11: Mean attitude scores of respondents towards VOLTA. The negative attitude region lies below the dotted line.

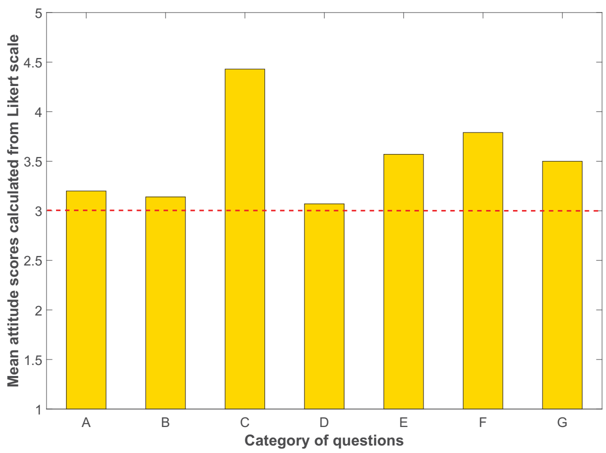

Fig. 12: Mean attitude scores towards each category of questions. The negative attitude region lies below the dotted line.

students thought the VOLTA Youtube channel was useful. The students indicated that the instructional videos were the most helpful features of VOLTA. In category E, two questions were asked regarding the authenticity of virtual learning. 57% of the students felt the labs seemed like a real lab. In category F, two questions were asked to assess the quality of the videos and VOLTA overall. In both cases, 85% of the students agreed the videos were of good quality and VOLTA was trouble-free. In category G, two questions were asked about the expectations from VOLTA. 56% of the students expected a feature to verify their simulation results in VOLTA.

B. *Effectiveness*

A total of 28 students participated in this study in Spring 2015. The experimental group consisted of 18 students, while the control group consisted of 10 students. The experimental and control groups were taught on a different day and time of the week. The experimental group received traditional laboratory teaching and assistance along with VOLTA. On the other hand, the control group was taught in a traditional manner only. A total of eleven lab assignments were performed in eleven weeks. In each of the lab assignments, there was a pre- and post-lab test. The pre-lab test comprised five questions in multiple choice format. Each question carried 20 points. The post-lab test comprised the same five questions with the multiple choices in different order. The same instructor taught both sections. Tables I and II show the pre-test and post-test scores of the control and experimental group of students. The average gain is the difference between the mean post- and pre-test score.

Fig. 13 shows the plots of pre-test and post-test score versus lab assignment index and average gain versus lab assignment index. From the figure, it can be seen that students taught by VOLTA performed significantly better in lab assignments 2, 3, 4, 5, 6, 7, 8, 9, 10, whereas traditionally-taught students scored better in lab assignments 1 and 11.

A two-group pre-test/post-test design approach was used to evaluate the effectiveness of VOLTA. The major question guiding the evaluation of VOLTA's effectiveness on learning: Did the students who used VOLTA (experimental group) learn more (e.g. score higher on gain measures) than their counterparts in the control group? The gain score analysis approach was used to analyze data from the two-group pre-test/post-test research design. The gain score is defined as the difference between the post-test and pre-test score. The null hypothesis is that there is no difference among the mean gains of the experimental and control groups for eleven assignments. The ANOVA test [24] was performed on the gain scores of 28 students in 11 lab assignments. The ANOVA test was performed using R (version 3.1.2). The $p < 0.001$ indicated that the null hypothesis can be rejected. In other words, there is sufficient evidence that the students taught with VOLTA performed better than their counterparts in the traditional labs. The differences are statistically significant at a confidence level of 95%.

VI. Discussion

The results from this study were encouraging and showed the benefits and challenges of VOLTA. The effectiveness assessment showed VOLTA students performed better than those of traditional lab students in eleven pairs of similar tests. VOLTA students were taught in a similar way as the traditional lab students, except without any handouts. Outside the lab, VOLTA students obtained help from VOLTA any time and from TAs during office hours. The traditional lab students got help from TAs only. VOLTA students received a greater amount of help compared to the traditional students, which was reflected in the effectiveness analysis.

The Spring 2015 version of VOLTA achieved $p < 0.001$, which was much better than the Fall 2014 version ($p = 0.117$). The Spring 2015 version of VOLTA had one new feature "Hardware Help", which provides a hardware assembly instructions based on Multisim netlist. Also, the Help module of Spring 2015 version of VOLTA had more questions and answers included. In Fall 2014, VOLTA was used for the first

TABLE I: Control Group's ($n = 18$) Pre-test and Post-test Score

	Pre-test		Post-test		Average gain
Lab Assignment no.	Mean	Standard Deviation	Mean	Standard Deviation	
1	61.11	19.40	68.89	15.23	7.78
2	48.89	23.31	54.44	8.96	5.56
3	67.06	13.62	68.24	13.82	1.18
4	74.44	26.50	83.33	30.73	8.89
5	85.56	17.39	84.44	15.71	1.11
6	77.78	22.00	77.78	20.96	0.00
7	54.44	23.86	47.78	23.23	6.67
8	76.67	30.00	81.11	27.06	4.44
9	85.56	17.39	83.33	17.95	2.22
10	54.44	28.91	54.44	29.67	0.00
11	47.78	20.15	48.89	20.25	1.11

TABLE II: Experimental Group's ($n = 10$) Pre-test and Post-test Score

	Pre-test		Post-test		Average gain
Lab Assignment no.	Mean	Standard Deviation	Mean	Standard Deviation	
1	68.00	16.00	76.00	8.00	8.00
2	44.00	12.00	56.00	12.00	12.00
3	76.00	12.00	88.00	9.80	12.00
4	54.00	20.10	66.00	26.91	12.00
5	84.00	24.98	90.00	18.44	6.00
6	76.00	26.53	90.00	18.44	14.00
7	62.00	10.77	68.00	9.80	6.00
8	70.00	28.64	84.00	14.97	14.00
9	70.00	18.44	96.00	8.00	26.00
10	56.00	24.98	74.00	20.10	18.00
11	74.00	15.62	76.00	14.97	2.00

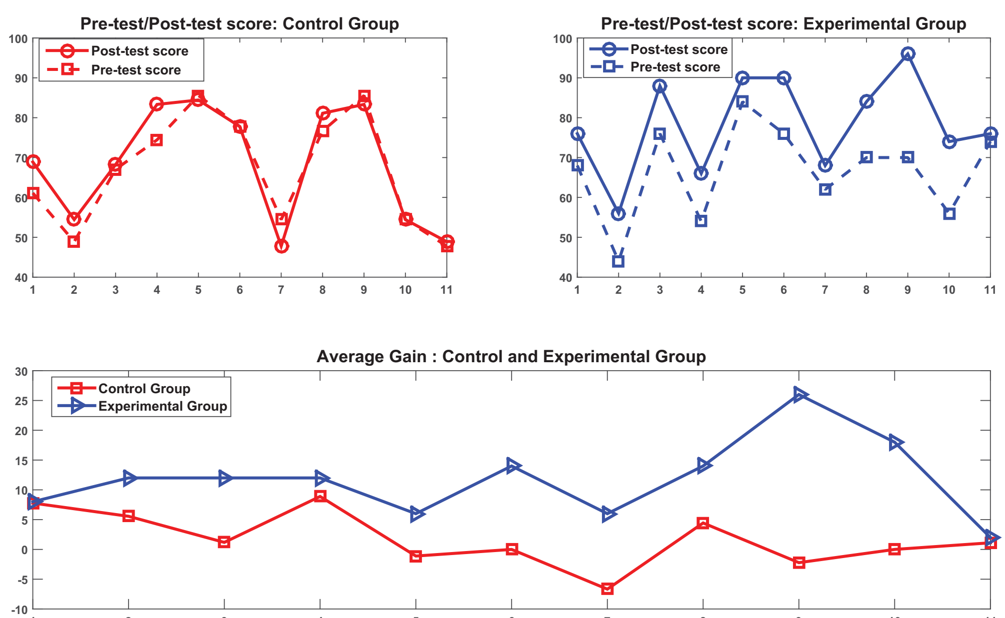

Fig. 13: Pre-test and Post-test score of Spring 2015.

time. The feedback in Fall 2014 enriched the Spring 2015 VOLTA, which resulted into a positive outcome.

The survey and in-class discussion showed that the students require some time to use the VOLTA efficiently, but the period was fairly short. After the fourth week, VOLTA students seemed to learn more, which was reflected in their post-test results from Lab 5. The students also felt that a verification of their simulation and hardware circuits would help them to a great extent. That justified the development of a circuit recognizer for VOLTA. With the circuit recognizer functionality, VOLTA will reduce the dependency on TAs.

Finally, the implementation of VOLTA initially requires a substantial amount of time. Creating lab contents and videos required a significant portion of time. Additional time was required to identify the questions the students might ask during the lab. Once the course material was developed, the TAs do not have to spend much time before each lab compared to the traditional lab. Most of the course materials are reusable. Therefore, in future semesters, VOLTA will reduce TAs workloads.

VII. Conclusion

VOLTA is an intelligent system for providing the students with an open laboratory environment equipped with virtual teaching assistance. VOLTA provides a self-paced environment, on-demand help, and increasing levels of engagement. The students gave positive feedback on various VOLTA content, such as instructional videos, safety videos, and short topic explanations. The students taught by traditional lectures and VOLTA were compared using the pre- and post-test performance. The ANOVA test showed $p < 0.001$ indicating VOLTA had a significant effect on students' performance. An advanced version of VOLTA development is currently in progress, which will feature a functional circuit simulation checker. Also, the speech module development is in progress, which can be helpful in detecting user frustration and offering assistance. These functionalities will decrease user frustration thereby enhancing the user experience.

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