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Work-in-Progress: Rapid Development of Advanced Virtual Labs for In-Person and Online Education

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Dr. Charles I. Sukenik is a Professor at Old Dominion University (ODU) and Chair of the Department of Physics. He earned a B.A. in physics from Cornell University in 1987 and a Ph.D. in physics from Yale University in 1993. Following post-doctoral appointments at the University of Michigan-Ann Arbor and the University of Wisconsin-Madison, he joined the ODU faculty in 1997. His current research activities are mainly in the areas of experimental, ultracold atomic and molecular physics; laser science; and applications of remote sensing to oceanography and supersonic flow diagnostics. He has also conducted research in other areas of physics including cavity quantum electrodynamics, quantum chaos, and ultrafast science.

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Brian Sanders has served in a variety of positions to include aircraft weapon systems technician, acquisition officer, and several senior scientific positions within the United States Air Force. His scientific background includes basic and applied research in developing new system capabilities in gas turbine engines, hypersonic flight vehicles, and unmanned aerial systems (UAS). Specific contributions in these areas involved research in high temperature composite materials, adaptive structures, and vehicle design. Dr. Sanders also led multi-organizational programs to bring high quality technical information early in the acquisition timeline via qualitative decision making tools and state-of-the-art modeling and simulation techniques. This was used by the USAF to initiate program requirements for the next generation of UAS. He has published over 70 journal articles, conference publications, and technical reports. Brian has taught aerospace engineering courses at the undergraduate and graduate level to include: aircraft structures, aerodynamics, aircraft performance, aeroelasticity, and adaptive structures, and I have advised Masters' and Doctoral students in pursuit of their graduate studies. EDUCATION 1985 Bachelor of Science Degree in Aerospace Engineering, University of Southern California 1987 Master of Science Degree in Aerospace Engineering, University of Dayton 1993 Doctor of Philosophy Degree in Aerospace Engineering, Air Force Institute of Technology 2020 Master of Science Degree in Modeling and Simulation 1980 Basic Military Training School, Lackland AFB, TX 1985 USAF Officers Training School, Lackland AFB, TX 1992 Squadron Officers School, Maxwell AFB, Ala 2006 Emerging Leaders Program, University of Dayton, OH 2008 Air War College CAREER CHRONOLOGY 1980-1982 Weapon Systems Technician, 479th AGS, Holloman AFB, NM 1982-1983 Weapon Systems Crew Chief, 479th AGS, Holloman AFB , NM 1985-1987 Logistics Engineer, Strategic Systems Program Office, Wright Patterson AFB, OH 1987-1989 Logistics Engineer, Short Range Attack Missile II Program Office, Wright Patterson AFB, OH 1992 -1995 Researcher, High Temperature Composite Materials Branch, Air Force Research Laboratory, Materials Directorate, Wright Patterson AFB, OH 1995-1999 Program Manager, Structural Mechanics Program, Air Force Office of Scientific Research, Washington DC 1999-2002 Senior Research Scientist, Air Force Research Laboratory, Air Vehicles Directorate, Wright Patterson AFB, OH 2002- 2008 Adaptive Structures Team Leader, Air Force Research Laboratory, Air Vehicles Directorate, Wright Patterson AFB, OH 2008-2013 Assistant Chief Scientist, Air Combat Command, Langley AFB, VA 2013-present Embry-Riddle Aeronautical University, Worldwide Campus AWARDS AND HONORS Honor Graduate Basic Military Training Honor Graduate Weapon Systems Technical School Inspector General Award for Management of SRAM II Logistics Engineering Program Associate Fellow, American Institute of Aeronautics Sigma Gamma Tau (National Aerospace Honor Society) Tau Beta Pi (National Engineering Honor Society) PROFESSIONAL SOCIETY MEMBERSHIP AND SERVICE American Institute of Aeronautics and Astronautics (AIAA) American Society of Mechanical Engineers (ASME) American Society of Engineering Education (ASEE) Vice Chair ASME Aerospace Division Executive Committee ASME Adaptive Structures and Material Systems Technical Committee AIAA Structures Technical Committee Engineering Program Advisory Committee, United States Air Force Academy Associate Editor, Journal of Intelligent Material Systems and Structures

Justin Mason

Justin Mason joined ODU in 2012 where he started as the Academic Support Coordinator for the Physics Department. In 2015 he also became the director of ODU's planetarium. While at ODU, Justin has earned several awards including Rookie Staff Member of the Year in 2013. He received an M.S. in Physics from Ball State University and an M.S. in Astronomy from Indiana University. His research included observational techniques for detecting red dwarf stars and computer simulations predicting the behavior of the outermost layers of neutron stars.

Work-in-Progress: Rapid Development of Advanced Virtual Labs for In-Person and Online Education

Abstract
During the closure of K-12 schools and universities due to the COVID-19 pandemic, many educators turned to web conferencing tools such as Zoom and WebEx to deliver online lectures. For courses with labs, some teachers provide recorded videos of real labs. Watching recorded lab videos is a passive experience, as the procedures and point of view are fixed, and students do not have any control of the lab and thus miss the opportunity to explore different options, including making mistakes that is important part of the learning process. One approach that holds great potential to enhance laboratory experience for online education is the use of computer-based modeling and simulation tools. Simulation based virtual laboratories emulate lab equipment and configurations in highly realistic 3D environments and can provide very effective learning experiences. While there exist limited interactive lab computer simulations for various subjects, their presentations are still very primitive and often lack realism and complexity.

This paper presents methodologies and preliminary findings on rapid development of advanced virtual labs using modeling and simulation for in-person and online education. The importance of modeling and simulation has long been recognized by the scientific community and agencies such as DoD and NSF. However, high-quality simulations are not commonplace, and simulations have not been widely employed in education. Existing simulations for education lack interoperability and compatibility. While there are sporadic uses of computer-based simulations in education that were developed in a piecemeal fashion, there was never systematic development at an industry level for such purposes. Virtual lab development usually require substantial amount of effort and lack of systematic research on rapid virtual lab development hinders their wide use in education. This paper proposes a wholistic and systematic approach for addressing the issues in rapid lab simulation development from several perspectives, including rapid generation of virtual environment, integration of state-of-the-art industry leading software tools, advanced software design techniques that enables large scale software reuse, and innovative user interface design that facilitate the configuration and use of virtual labs by instructors and students. This paper will implement a virtual circuit lab that emulates a circuit lab for the course PHYS 303 offered at Old Dominion University and will be used to elucidate the crucial methodologies for rapid virtual lab development. The virtual lab contains highly realistic visual renderings and accurate functional representations of sophisticated equipment, such as digital oscilloscopes, function generators, and digital multimeters, and authentic rendition of the lab space. The virtual lab allows analog and digital circuit simulation by integrating the de-facto industry standard circuit simulation engine SPICE and Xspice, supporting the circuit labs in course PHYS 303. The Unity game engine is used to develop the front end of the virtual lab. Advanced software development methodologies will be investigated to facilitate software reuse and rapid development, e.g., the same simulation code can be used to support equipment manufactured by different vendors. The paper will also investigate the impact of fidelity of the virtual lab, e.g., equipment and lab room, on student learning outcomes and efficacy.

1. Introduction

Online education becomes more and more accessible thanks to the advancement in computing technologies such as networking. During the COVID-19 pandemic, many universities turn to online conference tools such as ZOOM and WebEx. Online educational resources are usually more applicable for teaching theories or concepts, such as teaching theorems or solving equations. However, instructors and students have a relatively negative experience with courses involving labs. In most cases, instructors use live streams or recorded videos for lab demonstrations. However, live stream or recorded video does not allow the learner to participate in the experimental process, thus the content and concepts learned by the students are limited. In science and engineering education, laboratory experiments are important components because they set the stage for practical experience in understanding theoretical concepts or directly solving real-world problems. Students often gain more experience and knowledge from experimental labs than from purely theoretical lectures. Computer-based modeling and simulation (M&S) methodologies have great potential to address this issue. By building highly realistic 3D teaching environments that emulate the real classroom, in which the equipment and tools needed for experimentation are configured and equipped, students not only can obtain an authentic learning experience, but can also avoid potential hazards on human or equipment involved in the labs. For instance, Students may accidentally build a short circuit in the virtual lab, visual feedback such as explosion effect or warning message can be prompted, students will then avoid making a similar mistake again in the real lab.

Computer-based modeling and simulation allow users to actively explore the virtual environment and acquire knowledge and skills. Many scholars have conducted research on the impact of computer-based modeling and simulation on education. Butt’s group discussed the method that was using computer-based modeling and simulation in nurse education for training purposes [1]. Kim and his group conducted a control experiment on 132 elementary school students and concluded that online learning in virtual environment has a significant positive impact on the mathematical performance of elementary school students [2]. Medical students can safely practice surgeries in virtual environment [3]. The benefit of virtual lab not only meets the needs of online education or distance learning, but traditional in-person instruction also benefits from virtual labs, as students do not have to wait until the lab session to operate the equipment, pre-lab preparation can be done at home by following step-by-step instructions.

This paper presents the development of a highly realistic 3D virtual lab environment for learning experimental physics. The latest design and development of the virtual lab for electronic circuits is presented. The software is designed based on the labs for the course PHYS 303 Intermediate Experimental Physics offered by Old Dominion University. Topics covered in this course include basic electronics with an introduction to diode, transistor, and op-amp circuitry, and an introduction to physical computing using LabView and Arduino microcontrollers.

The remaining of this paper is organized as follows. Section 2 introduces the physics lab to be modeled and simulated in this work. Section 3 presents the methodology of the current version of the virtual lab. Section 4 describes the current results of the virtual lab. Section 5 discusses future work and concludes the paper.

2. Background

In late 1995, the Department of Physics at Old Dominion University began to take a more standardized approach to undergraduate laboratory instruction, and in 1996 the department published the first edition of a department-wide undergraduate laboratory manual. The approach to teaching undergraduate physics at Old Dominion University shifted from the traditional experimental approach to the use of computer-assisted data collection techniques. The development of virtual labs will allow for the further refinement of this pedagogy. For example, the pre-defined teaching materials including the virtual labs will allow instructors to follow the same teaching standards and thus afford consistent learning experiences to students.

PHY 303 Intermediate Experimental Physics is a laboratory course for sophomore and junior students. The lab equipment and devices include oscilloscopes, signal generators, high pass and low pass filters, sine signal and AC circuits, diode, operational amplifiers, operational amplifiers with feedback, and transistors. A picture of the lab used by PHY 303 is shown in Figure 1. Note that the lab layout is slightly different compared to the PHY 303 lab session since it was being used for another course at the time the photo was taken.

Figure 1. Physics Lab of the Department of Physics at Old Dominion University

The instruments used in this lab include an oscilloscope, a digital multimeter, a DC power supply, a digital/analog trainer, and a function generator. Figure 2 shows the instruments used in PHYS 303.

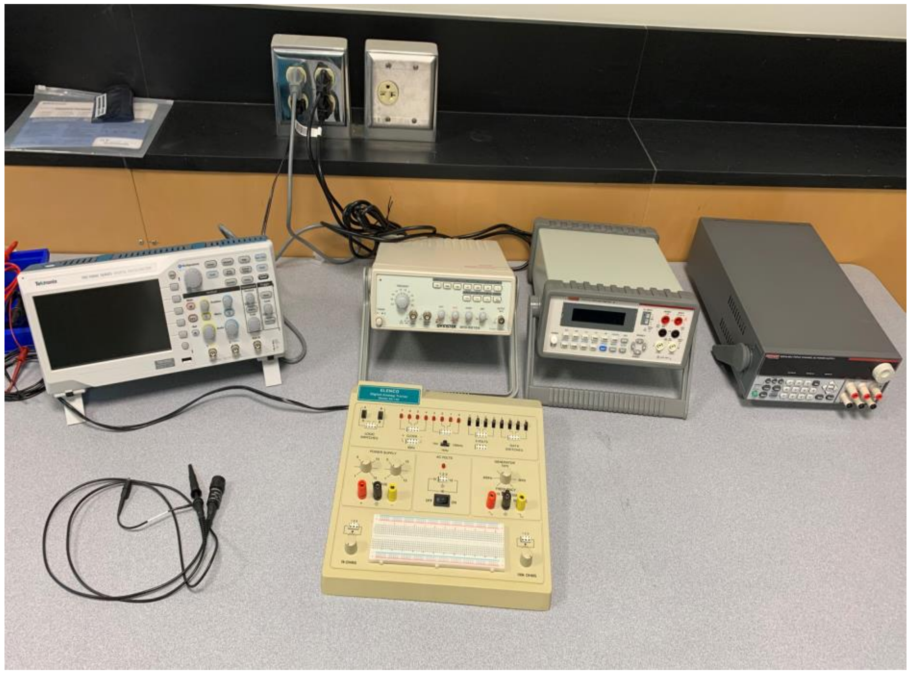


Figure 2. Instruments used in PHY 303

A key device in the PHYS 303 lab is the digital/analog trainer (shown at the lower part of Figure 2), which is a complete mini-lab for building and testing analog and digital circuits that contains the following five main sections [4].

- The digital trainer section located at the top of the trainer, consisting of a clock generator, two no-bounce logic switches, eight LED indicator lamps, and eight data switches.
- The DC power supply section is located at the trainer's middle-left section; it provides up to +15 V and -15 V DC voltage at 0.25 A.
- The AC power supply section is at the center of the trainer, and it supplies a 30 V AC.
- The function generator section is at the middle-right part of the trainer that can provide sine and square waveform; the frequency is from 200 Hz to 40,000 Hz.
- A breadboard and two undedicated potentiometers are at the bottom of the trainer.

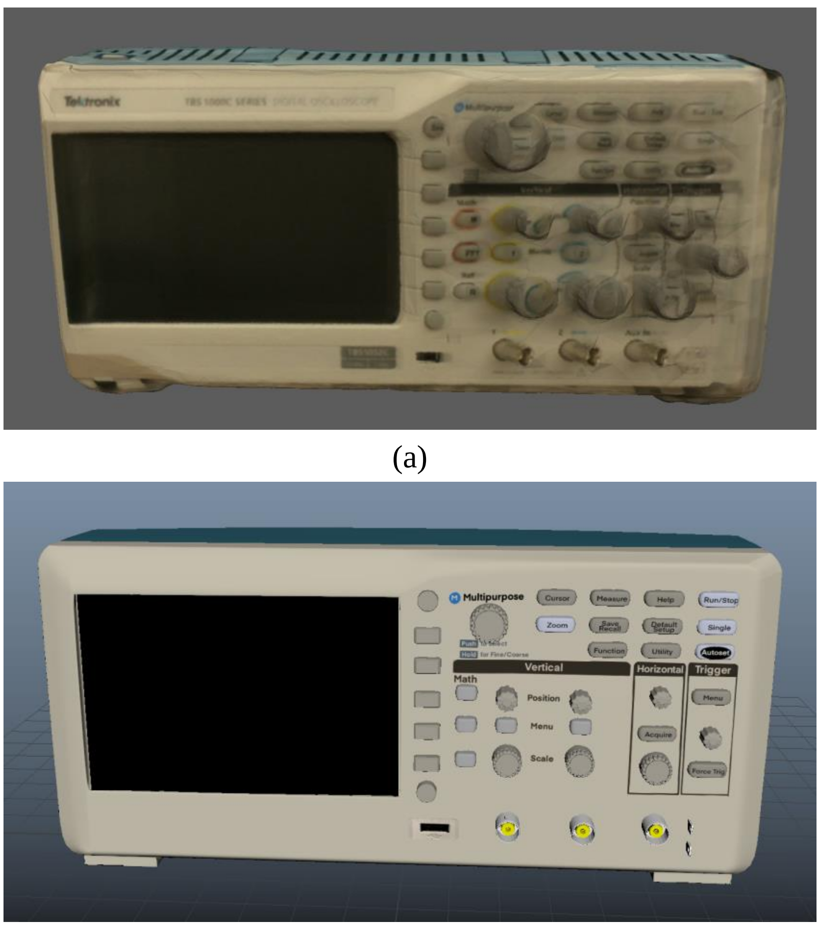
The modeling and simulation of the laboratory start with the modeling of instruments. At the current stage, we have modeled the oscilloscope and digital/analog trainer.

3. Methodology

A. 3D Modeling and Software Development

Three-dimensional (3D) modeling is the technique in computer graphics for creating a digital representation of an object. Modeling software is used to manipulate vertices in virtual space to form a mesh. These 3D objects can be generated by deforming, manipulating, or sculpting the mesh. 3D modeling is used in many industries such as films, video games, engineering, and commercial advertising.

3D modeling is a complex and time-consuming process that requires significant training. Various approaches can be used to create the models for instruments, devices, and lab space used in the lab. For example, a 3D model for the oscilloscope can be generated from scratch, with a very tedious process that consumes enormous time and thus is not very feasible. Another option that is gaining more popularity is to scan the real-world objects first and then generate the 3D models of these objects based on their scans. The last decade has witnessed advancement of various 3D scanning technologies, such as structured-light, LiDAR, and time of flight, thanks to emerging hardware and software technologies. This work utilizes the Structure Sensor [5], a handhold 3D scanner that is attached to an iPad, to scan the lab instruments. The Structure Sensor generates 3D meshes, such as the one for an oscilloscope shown in Figure 3 (a). Such meshes don't provide sufficient resolution and fidelity to be used in the virtual directly. Instead, they are used as a reference for the 3D modeling. Figure 3 (b) shows the final model that was generated based on the scanned model. The proposed 2-step modeling process based on 3D scanning significantly reduces the time needed and greatly enhances the quality and fidelity of the final 3D models. This approach should be utilized for modeling most real-world objects in the virtual lab.



(a)

(b)

Figure 3. 3D models of an oscilloscope. (a) The original 3D model directly generated by the Structure Sensor. (b) The final 3D model that was generated using Maya based on the original model.

The models were generated using Autodesk Maya, an industry-leading 3D modeling and animation software that runs on Windows, macOS, and Linux. It can be used to create assets for interactive 3D applications, including video games, animated films, TV commercials, and visual effects. Figure 4 shows the model of the digital/analog trainer generated with Maya.

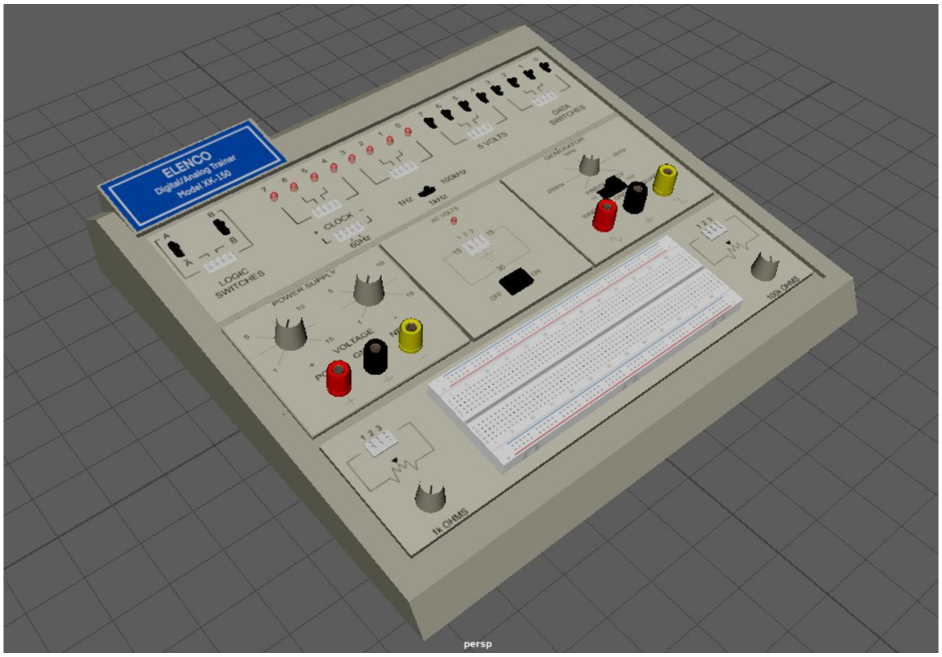


Figure 4. 3D model of the digital/analog trainer

The Unity Engine was utilized as the major tool for software development in this work. Unity is a leading game engine for cross-platform game and interactive simulation development with a wide range of advanced capabilities, such as rendering, physics engine, animation, virtual reality, and augmented reality [6]. The overall software architecture of the virtual lab is shown in Figure 5. It contains the following major modules or functionalities.

- **User Interface** contains the graphical representation of the lab environment. Multiple environments will be implemented to suit the experiment requirement of the individual lab session. In the later stage, the project will investigate the efficacy of the virtual labs as a function of fidelity levels. For example, one virtual lab environment will be set exactly the same as the real lab in terms of space, table layout, and instrument layout.
- **Lab Instructions** contains instructions of all lab sessions, including step-by-step explanation on experiment procedures and instruments, video demonstrations, and lecture handouts, etc. It also provides the interface for instructors to customize the instruction content according to course needs.
- **Component Management** handles the circuit components, and it has references to all the components used in the current lab.
- **Circuit Build Module and Circuit Topology Extraction Module** contains two essential parts: a) a circuit connection management engine that manages the circuit connections. The core component in the circuit connection engine is the management of nodes and connector between instruments, wires and circuit components, b) a SPICE script

generation engine that interprets the circuit connectivity, determines the topology of the circuit, and then generate the SPICE script input that is used in Circuit Simulation Module.

- **Circuit Simulation Module** uses SPICE as the simulation engine. It receives SPICE scripts generated from the previous module, execute the simulation, and produces simulation results. SPICE will be introduced in the next subsection.
- **Instrumentation Module** provides simulation of instruments such as oscilloscope and multimeter. It handles user's inputs to the instruments, computes the measurement selected by the user based on circuit simulation results, and display the measurements on the virtual screen of 3D models such as oscilloscope and digital multimeter.
- **User Data Management** manages user accounts so that the use of the virtual lab can be recorded for individual users. It facilitates instructors to review the experimental steps and operations performed by students.
- **Result Module** is used to manage and display the experimental results. Different from the Instrumentation module, the results module can display the results outside an instrument. For example, the experimental results can be displayed directly above a circuit component by means of tooltips. Such varied modalities for result display provides students different means of learning and thus can facilitate learning at different cognitive levels.

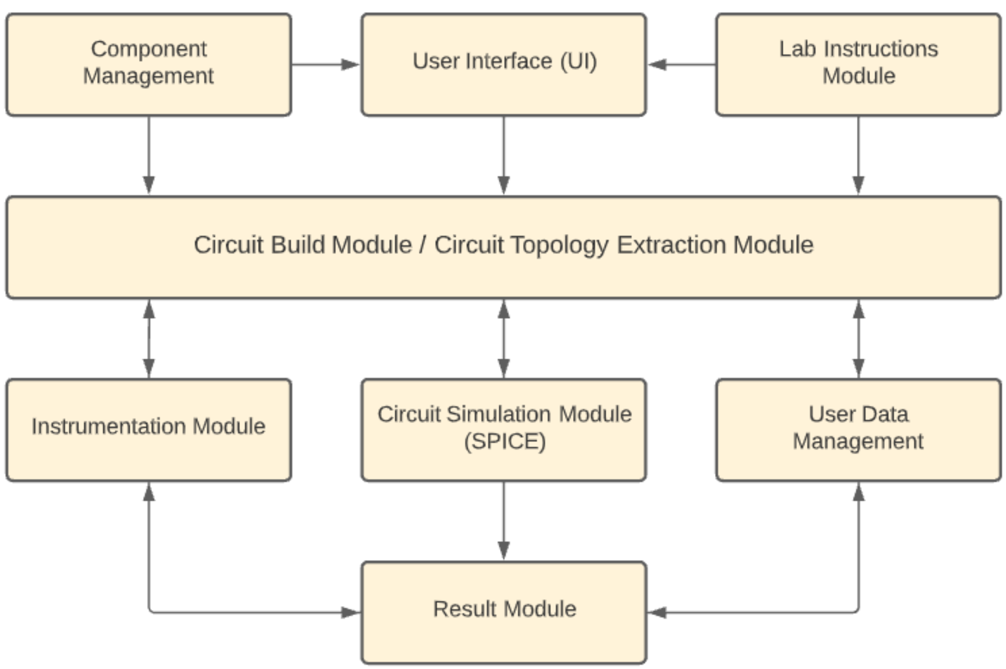


Figure 5. Software Architecture

B. SPICE

The backend circuit simulation engine for the virtual lab in this work is SPICE (Simulation Program with Integrated Circuit Emphasis), an open-source general-purpose analog circuit simulator [6]. It is the most widely used program for circuit design and circuit simulation in academia and industry. SPICE was originally derived from a program named CANCER at the Electronics Research Laboratory at the University of California, Berkeley, by Dr. Laurence Nagel. It contains three main circuit analyses: a) non-linear DC analysis, b) small-signal, sinusoidal steady-state analysis, and c) non-linear, time-domain, transient analysis. SPICE adopted the Sparse Matrix Solver to reduce storage requirements and improve execution efficiency [6]. In 1975, Dr. Nagel's thesis introduced SPICE2 to the public. SPICE2 implemented Modified Nodal Analysis, a method that is the cornerstone of today's circuit simulation software [7]. SPICE1 and SPICE2 uses FORTRAN as their programming language. In 1985, Thomas Quarles from U.C. Berkeley rewrote SPICE2 in C and released SPICE3 [8]. The latest version of SPICE is version 3f5, released in 1993 [9].

SPICE source files are text-description of the circuit components and are commonly referred to as netlists. Netlists describe the topology of the circuit components; for example, an independent DC voltage source is described as <Vxxx> <N1><N2><Type><Value>, where Vxxx stands for the voltage source named xxx. N1 and N2 are two terminal nodes of the voltage source. Type and value specify the source type and value of the component. This paper uses LTspice simulator to generate the circuit simulation example. LTspice [10] is one of the best SPICE software on the market. A simple circuit example is presented below. Figure 6 shows the schematic diagram of the circuit, and Figure 7 shows the Netlist input and simulation result of the circuit.

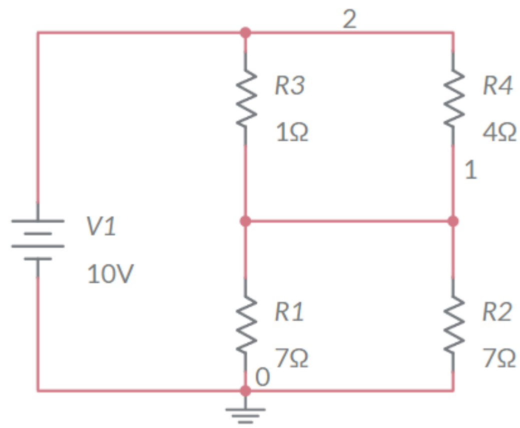
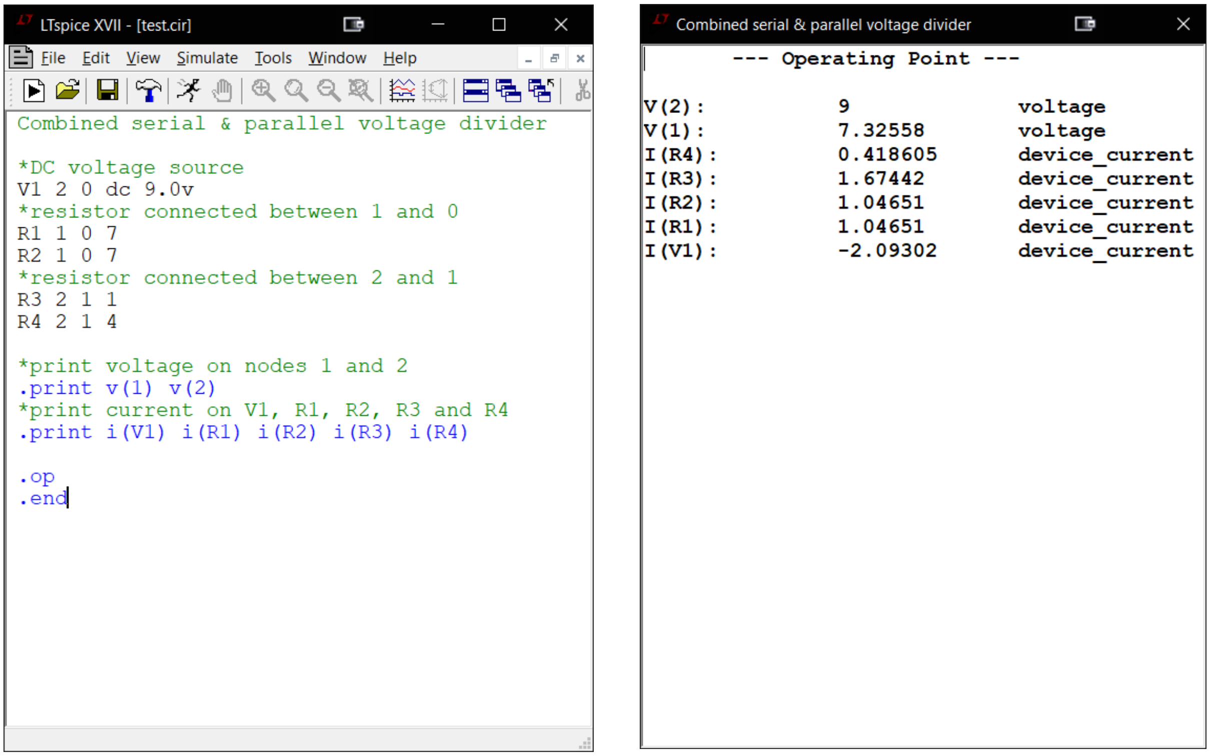


Figure 6. Schematic Diagram of an example circuit



(a) (b)

Figure 7. Circuit simulation using LTspice. (a) LTspice circuit simulation input. (b) Ltspice Simulation output.

Circuit simulation tools such as Multisim [11] and Circuit Lab [12] provide a user-friendly interface that allows the user to design the schematic first, and then a netlist is automatically extracted from the schematic to simulate the circuit. Fritzing is an open-source hardware initiative to facilitate hardware development [13]. Its software tool, also named Fritzing, provides a more user-friendly graphical interface. In addition to its schematic capture, Fritzing also provides a visual representation of the circuit components, such as breadboard, diode, and resistor. A visual representation is certainly more friendly for beginners. However, Fritzing lacks the implementation of simulation functionality, and it only provides a 2D view (top view) of the circuit components. One serious problem for 2D view is that for a complex circuit design that consists of many components, the connection sockets of the breadboard can be obscured by electronic components. A 3D view can solve this problem by providing different perspectives, enabled by 3D user interactions, such as orbiting. The program will analyze the circuit topology based on the design results, generate schematic diagrams, and analysis results.

4. Current Results

A virtual lab prototype capable of handling circuit components connection logic has been developed. The virtual lab prototype allows user to place circuit components and connect circuit components, to a breadboard, and to place jump wires between instruments by clicking the two terminals (ends) of the instruments. The shape (path) of the jump wire can be changed during wire generation. The texture of the resistor component is generated automatically based on its resistance and the 4-band resistor color code. Figure 8 shows the breadboard and simple connection between components, as well as the resistor color code, the resistances from top to bottom, left to right are 7 ohms, 7 ohms, 1 ohm, and 4 ohms. The combined series and parallel voltage divider example used here is the same as in the LTspice simulation in Figure 7 to demonstrate the simulation result.

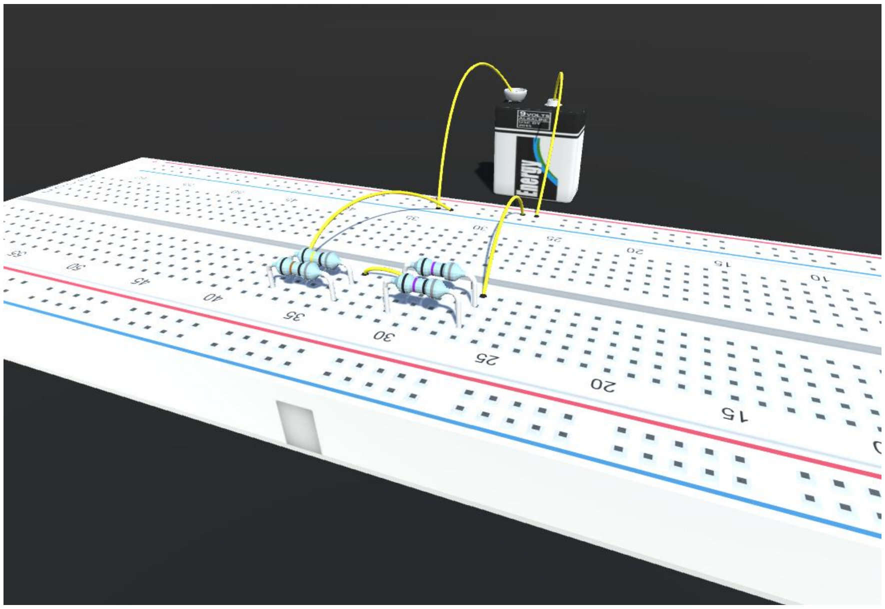


Figure 8. Circuit component connection and resistor color code example

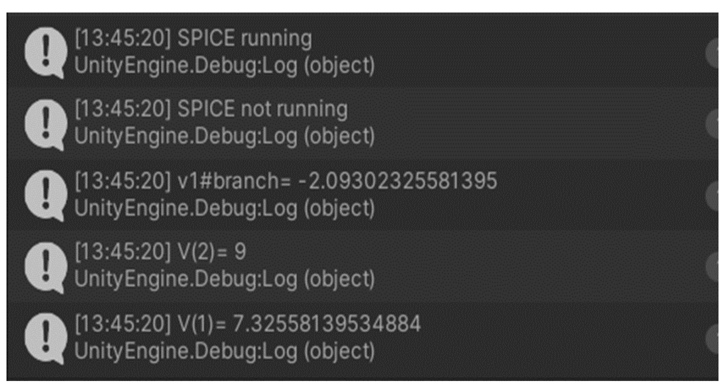
The virtual lab is able to perform circuit simulation on currently supported circuit components; more circuit components will be added in the future. The program retrieves and collapses connected nodes in the circuit, determines the circuit topology, generates a list of strings for SPICE input, and receives the result from SPICE simulator. Figure 9 shows the generated script input for SPICE simulator and the simulation output. The simulation result shows the voltage at node 2 is 9V and at node 1 is 7.33V, and the current through the voltage source is 2.09A.

```
Combined series & parallel voltage divider

*resistor connected between nodes 1 and 0
R1 1 0 7
*dc voltage connected between nodes 2 and 0
V1 2 0 dc 9
*resistor connected between nodes 1 and 0
R2 1 0 7
*resistor connected between nodes 2 and 1
R3 2 1 1
*resistor connected between nodes 2 and 1
R4 2 1 4

.op
.end
```

(a)



(b)

Figure 9. (a) The SPICE script generated from the circuit. (b) The simulation output.

5. Conclusion and Future work

The current stage of the virtual lab implements the extraction of the circuit topology, the generation of SPICE scripts, and the interaction with the SPICE simulator. Ongoing work includes 3D and functional modeling of lab instruments such as the oscilloscope and the digital/analog trainer. In future work, the real labs will be modeled, as well as the design and implementation for the different sections of the lab course content. The virtual version of oscilloscope, digital multimeter, DC power supply, etc. will be implemented to support the labs. Technologies for rapid software development and code reuse will be explored. For example, the code for the simulation of the oscilloscope can be used for oscilloscopes produced by different manufacturers. VR versions and web-based virtual labs will also be developed to address the diverse needs of different instructors and learners.

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