Virtual Circuits: An Augmented Reality Circuit Simulator for Engineering Students

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Abstract—The abilities of Augmented Reality to overlay learning materials with contextual dynamic information and of software simulations to allow rapid and safe exploration of complex engineering concepts have already been established as beneficial in education. Access to both technologies in the classroom has been rather limited due to costs and hardware requirements. With the intention to bring these two technologies closer to engineering students, we created Virtual Circuits: a low-cost simulator app of electrical circuits designed for the classroom and autonomous study. Virtual Circuits requires only a smartphone and a set of plastic tokens and, with the help of Augmented Reality and a simulation engine, it allows electrical engineering students to quickly explore complex concepts in their field. In this article we present the Virtual Circuits app and the results of our first field test in a real electrical engineering classroom at our university. The collected feedback from students was overwhelmingly positive hinting at tangible educational benefits and improvements in future versions of our app.

Keywords-Augmented Reality; Education; Circuit Simulation.

I. INTRODUCTION

The educational benefits of information technologies such as software simulations and virtual laboratories are already well documented and understood [1]. Moreover, educational applications of newer technologies such as Augmented Reality (AR), the superposition of context aware virtual information over a real world context [2], are currently finding their way in a plethora of learning environments [3] [4]. Recent findings suggest that the ability of AR-capable devices, from optical head-mounted displays to mobile phones, to overlay learning material with contextual visualizations leads to beneficial effects in learning [5]. In this article we present Virtual Circuits: a low-cost AR circuit simulator app for electrical engineering courses and explore its use in a real learning environment.

Virtual Circuits aims to be an educational electrical circuit simulator that runs on a student's mobile phone. The relatively small touchscreen on a mobile device is normally too cumbersome to interact with a software simulation; therefore Virtual Circuits is complemented with a tangible user interface (TUI) composed of plastic tokens and a paper sheet. The paper sheet represents an electrical circuit and the tokens the different electrical components and measurement devices normally used in laboratory exercises. The simulation's graphical user interface (GUI) interacts and overlaps with the TUI using AR. All elements in the TUI are overlaid with static graphical representations, dynamic simulation data, and additional GUI controls. Virtual Circuits was not designed to replace traditional laboratory exercises but rather to serve as a scaffold in the understanding of complex engineering concepts during lectures and autonomous study.

After several prototyping iterations, we tested Virtual Circuits with 100 students in their third year of electrical engineering in our university. Details and results of the experiment are presented in section IV and section V respectively. Section II scans the state-of-the-art in AR simulations for education and section VI presents conclusions from our first experience using Virtual Circuits in a learning environment.

II. RELATED WORK

This work is focused on the use of AR for educational purposes in engineering curricula. Previous studies have already considered using AR systems in this space. For example, Wojciechowski *et al* [6] developed an AR framework based on the *oriented-object paradigm* and used the *Technology Acceptance Model* (TAM) to show that it was perceived as useful during a chemistry experiment. Chen *et al* [7] used an AR system for electro-chemistry based on the *Experiential Learning Circle Methods* with two types of AR images: static and dynamic. Students that used static AR outperformed those who used dynamic AR. All of these described works report higher motivation of participants.

For laboratory sessions, Akçayir *et al* [2] investigated the use of AR on university science labs by implementing a tutorial system for physics experiments. Ibáñez *et al*, in two studies [8] [9], also used AR in laboratory sessions of basic electrical principles for 9th grade students. In these studies, the easiness to acquire knowledge, motivation, and usefulness are highlighted characteristics.

There are non-tested proposed methods for using of AR. Carolan *et al* [10] established a model for knowledge structuring in science and engineering intended to be used for lifelong learning, where virtual reality is a chosen topic, and augmented reality a step to test it. Santos *et al* [11], with expectations for future use, designed an AR-based educational method based on *IEEE learning objects* in an iterative process involving engineers, curriculum designers, teachers, and students to create *AR learning experiences* supported by *AR learning objects*.

The works so far mentioned used image-based tracking AR technology; however, there are more complex solutions such as in [12] and [13], where devices like *substances analyzers* for chemistry experiments and an optical head-mounted display

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Fig. 1. Virtual Circuits basic setup: The AR GUI and simulation engine run on the mobile device while a sheet of paper and a set of plastic tokens serve as the simulation's TUI.

for AR-based lectures are used. Low-cost AR solutions using smart-phones and tablets in learning environments are also explored in [6] [7] [2] [8] [9] [14].

Our work is intended to show user experience satisfaction and usefulness for a complex, but easy to use, system that integrates an electrical circuit simulator with AR components for teaching electrical networks' concepts to engineering students. This system is a *proof-of-concept* implemented under an accessible technology on smart-phones and tablets together with a low-cost TUI to facilitate the user interaction.

III. DESIGN

The main design objective of Virtual Circuits is to provide engineering students a learning scaffold for the understanding of complex electrical concepts using a low-cost AR-based system. As seen on Fig. 1, Virtual Circuits can be divided into two components: a digital environment with virtual objects (simulation engine, GUI); and a physical environment (sheet of paper, plastic tokens).

A. Physical Environment

The physical environment is the TUI of Virtual Circuits allowing the student to directly manipulate real objects that interact with the system's simulation. As observed in Fig. 1, the physical environment is composed of the following elements:

- A *paper sheet*, where a schematic of an electrical circuit is printed with a fiducial marker on its top-right corner that is used by the AR software.
- A set of 3D-printed *plastic tokens* with a piece of paper on its front face representing a fiducial marker that denotes an electrical element such as an specific resistor, voltmeter, or ammeter.

The circuit in the paper sheet is composed of fixed elements and gaps/slots to be filled with the plastic tokens to complete the circuit. In this particular example (Fig. 2), the fixed elements are resistors (R1, R2, R3, R5) and a DC voltage source
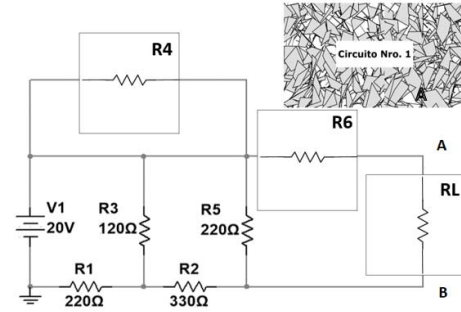

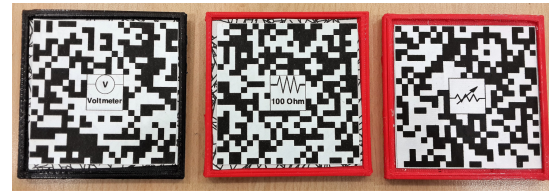Fig. 2. Electrical circuit schematic printout used in Experiment 1.

Fig. 3. Plastic tokens represent electrical components in the simulation.
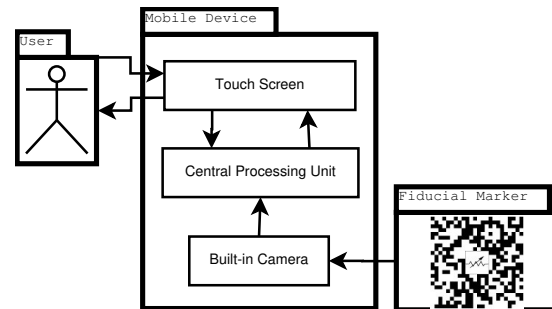

Fig. 4. Hardware components of the AR system

(V1). The slots (R4, R6, RL) are intended to be filled with the tokens according to the experiment instructions provided to students in this work and described in section IV. Some of the tokens (voltmeter, 100 Ohm resistor, and a variable resistor) are appreciated in Fig. 3.

After experimenting with several physical configurations, we determined that it was important for users to have their hands free to manipulate the TUI as well as the GUI. Consequently, as seen on Fig. 1, the physical environment needs to be placed on a flat table and the mobile device on a fixed stand.

Fig. 4 depicts how the mobile device interacts with its environment. The *user* interacts with the AR physical objects as well as the *touch screen* from the mobile device, which uses its *built-in camera* to collect the input from the *fiducial markers*. This data is *processed* by the computer vision algorithms to achieve the desired results, which are shown to the user on the screen.
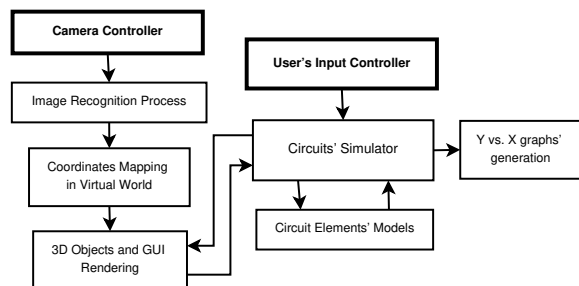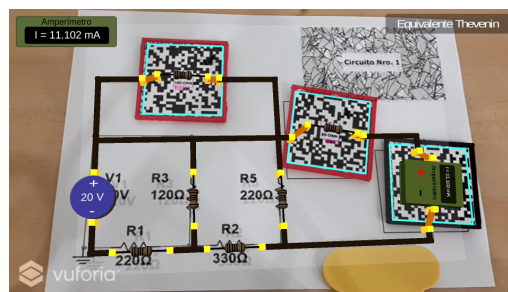
Fig. 5. Software components of the AR system

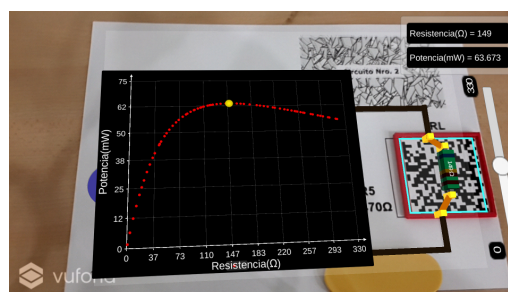Fig. 6. Virtual and Physical objects in the AR system: screen capture of the AR interface on the mobile device.

Fig. 7. Power vs. Resistance graph in the AR system: screen capture of an interactive visual component in the AR interface.

B. Virtual Environment

The virtual environment is supported by an AR software developed in the *Unity 3D Game Engine* using its Android plug-in together with the *Vuforia SDK*. These tools were mainly used for graphical purposes and AR requirements. For the electrical circuit simulation, the source code from the library project *SharpCircuit* [15] was integrated and combined with 3D models as electrical elements whose logic for the simulation is managed by this library. This AR software is able to simulate any circuit with DC or AC currents as well as some semiconductors; however, for this research, the components were limited to DC voltage sources, fixed and variable resistors, and multimeters (voltmeters and ammeters).

The software components of the AR system are shown in Fig. 5. This is a real-time system that collects data from the environment using the *camera controller* and an *image recognition* module. This last module identifies the fiducial markers to *map coordinates in the virtual world* inside the application and generate three-dimensional points in space that are adjusted to the identified marker. After this procedure, the system is then able to place the virtual object over the physical object using the *3D Object and GUI rendering* module as well as the *Graphical User Interface* (GUI) presented to the user on the device's screen. Additionally, a *Circuits' Simulator* module processes the algorithms for electrical networks which are applied over the *Circuit Elements' Models* such us sources, resistors, multimeters, etc. These elements are mathematical models that are being constantly updated to provide, for instance, voltages and currents values in a circuit that can be observed by the user. Furthermore, the information obtained by the simulator can be used to generate *Y vs. X graphs*, where Y and X depends on the intended learning goal (see for example Fig. 7).

A screen-shot from the mobile device's display presented in Fig. 6 illustrates the physical and virtual objects in which two resistors and one ammeter are used over a basic 3D virtual circuit. A GUI label is displayed in the top-left of the screen indicating the current (I) value from the ammeter. Users can connect/disconnect tokens from the circuit by placing them in the slots in the sheet of paper (automatic connection) or by tapping two tokens together (manual connection).

As explained before, the AR system can support graphs according to the learning needs. For this work, a *Power*

vs. *Resistance* graph was implemented as Fig. 7 denotes. When selecting the variable resistor, the learner can change the resistance value and see in real-time how it relates to power.

The presented configuration of Virtual Circuits went through several prototyping cycles due to the difficulty of providing an acceptable user experience. For example, the accidental occlusion of the fiducial markers by the user's hands or by other tokens caused the sudden disappearance of virtual objects, leading to data inconsistency issues and annoying interruptions to the learning activities. An acceptable compromise was to delay the removal of occluded objects, sacrificing the responsiveness of the simulation.

IV. MATERIALS AND METHODS

With the objective of exploring the usefulness of Virtual Circuits in a real learning environment, we designed two laboratory experiments based on electrical circuits' concepts: *Thevenin's Theorem* (Experiment 1) and *Maximum Power Transfer Theorem* (Experiment 2) considering the following learning objectives respectively:

- Explain how the *Thevenin Resistance* varies by changing the value of other resistances in an electrical circuit.
- Apply *Thevenin's Theorem* to determine the condition of load resistance to have the *Maximum Power Transfer*.

These experiments were carried out by students between 20 and 21 years old registered in the *Electrical Circuits Analysis II* course at our university (100 in total). The experiments were designed to be performed in pairs and we constructed three setups of Virtual Circuits, therefore each laboratory session

consisted of six students. Each session had an approximate duration of 45 minutes. Fig. 8 depicts two students during a laboratory session.

Before each session, students were given a laboratory guide (with tasks and details about both experiments) and a user experience survey. Their first task during the session was to answer a pre-test question in the survey and watch a short tutorial video (around 2 minutes) included in the Virtual Circuits app. To complete the session, the students finished the two experiments as explained below.

A. Experiment 1

The circuit used in this experiment is shown in Fig. 2 from section III. During this first part, students placed resistor tokens on the assigned slots with values according to a table provided in the laboratory guide. For each combination of resistors, students measured the Thevenin voltage (open-circuit voltage) and Norton current (short-circuit current) on designated points A-B. Then, the Thevenin resistance was calculated with both values.

B. Experiment 2

For this part, students calculated the Thevenin resistance by following the steps described in the first experiment. Afterwards, a variable resistor was placed on the same points where the Thevenin resistance was measured. A *Power* vs *Resistance* plot showed up just when the variable resistor was set (as seen on Fig. 7). The students were instructed to change the resistor value around the Thevenin resistance and register the showed power consumption to encourage them to determine in which resistance value the maximum power is obtained.

After the laboratory session, all students answered the post-test questions in the survey and completed a short quiz that measures the session's learning objectives. A total of 100 students participated in both experiments in the span of one week. Additionally, a sample of 11 students were selected to participate in a 5-minute interview after the two experiments. During the interview, the students were asked to elaborate further on their overall experience using Virtual Circuits. The results are presented in the next section.

V. RESULTS

We used two evaluation instruments to explore Virtual Circuit's effectiveness and usefulness: a survey to measure user experience and a short quiz to measure learning objectives.

A. Survey

We asked the students to answer a questionnaire composed of seven questions. The answer to each question ranged from 1 to 10, being 10 the maximum score. Except for question zero (pre-test), all the questions were answered after the test. This survey was made with the aim to measure the user experience while using the application from questions 1 to 6, including its usability and learning contribution to the user. The questions asked students to rate the following:
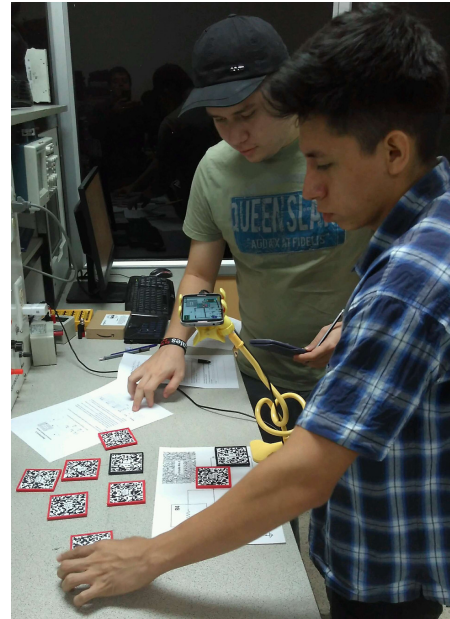

Fig. 8. Students interacting with the Virtual Circuits app during laboratory exercises.

TABLE I
DESCRIPTIVE STATISTIC FOR EACH QUESTION IN THE SURVEY

Question	Min.	Median	Mean	Max.	Std. Dev.
1	5.00	9.00	**8.91**	5.00	1.055
2	4.00	9.00	**9.04**	4.00	1.214
3	5.00	10.00	**9.10**	5.00	1.251
4	2.00	9.00	**8.46**	2.00	1.500
5	4.0	9.00	**9.15**	4.00	1.067
6	1.00	8.00	**7.62**	1.00	2.173

0) Familiarity with the Thevenin theorem in electrical networks.
1) Interaction experience with Virtual Circuits.
2) Motivation to use Virtual Circuits in your free time.
3) Usefulness of the Virtual Circuits as a learning tool for the performed experiment.
4) Learning perception of electrical network theory during session.
5) Usefulness of Virtual Circuits as a learning tool for other electrical network concepts.
6) Comparison of the AR-based session with traditional sessions.

The results for each question are shown in Fig. 9. The dimensions were split in three ranges as in [14]: excellent (10-9), acceptable (8-6), and bad (5-1). For all questions, except for question 6, an excellent score prevailed. The descriptive statistics for the survey are presented in Table I with emphasis on the *mean* for each question.

User experience survey results for 100 students

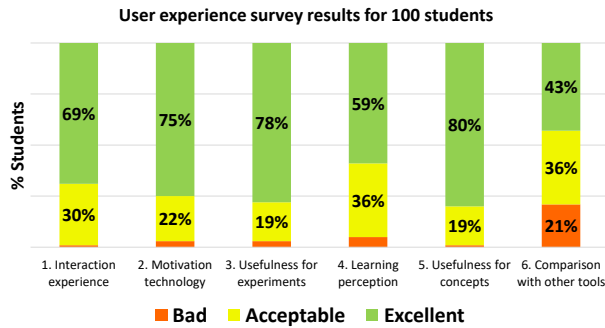|	1. Interaction experience	2. Motivation technology	3. Usefulness for experiments	4. Learning perception	5. Usefulness for concepts	6. Comparison with other tools
Excellent	69%	75%	78%	59%	80%	43%
Acceptable	30%	22%	19%	36%	19%	36%
Bad						21%

■ Bad ■ Acceptable ■ Excellent

Fig. 9. Aggregated survey results for 100 students. Six dimensions for user experience were measured and an excellent score prevailed in questions 1 to 5.

TABLE II
SUCCESS PERCENT ON QUIZ

Question 1	Question 2	Question 3	Question 4
96%	84%	79%	95%

B. Quiz

After all experiments were finished, a four-question quiz was taken in order to measure the learning objectives established in section IV. This quiz was composed by four choices per question with one only valid option.

The quiz was divided in two parts: three questions regarding variation of the Thevenin Resistance by changing other resistances' values, and one question about the condition of Maximum Power transfer. The results are shown on Table II

VI. CONCLUSION

After its first field test, Virtual Circuits was enthusiastically received by students and survey and test results point toward potential educational benefits. However, a larger test with a control group is still needed to establish if Virtual Circuits helps students reach their learning goals. Overall, students remarked on the ease of use of the application, educational value, and accessibility. They also suggested using the application for other complex concepts such as three-phase power circuits, transistors, and operational amplifiers. On the other hand, room for improvement still exists as students reported slow responsiveness and a crowded GUI. We envision Virtual Circuits as a digital magnifying glass that allows a learner to peek inside an electrical system; future versions will further exploit this capability by supporting more complex scenarios and components.

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