A sustainable approach to let students do more real experiments with electrical and electronic circuits

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ABSTRACT

The[1] present paper focus on the use of remote laboratories in higher education from a sustainability viewpoint. The particular case of engineering education, and, within it, the more specific subject of experiments with electrical and electronic circuits is presented first, to then discuss the benefits of using remote labs, while considering the three dimensions of sustainable development, i.e.: economic practice, environmental protection, and social integration. The paper debates how remote labs address each dimension.

CCS CONCEPTS

• **Applied Computing → Physical Sciences and Engineering**;

• **Applied Computing → Education**;

KEYWORDS

VISIR, remote labs, engineering education, sustainable higher education, experimental skills, electrical and electronic circuits

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1 INTRODUCTION

Engineers are expected to be well trained in experimentation. In fact, their training encompasses a large number of laboratory classes, where they acquire and practice their experimental skills. They obtain these skills by successfully completing a number of learning objectives associated with instructional laboratories in Engineering undergraduate curricula [1–3]. Some of these learning objectives imply a direct manipulation of objects under experimentation and test equipment available in the laboratory, e.g. objectives 5 and 7 listed in references [1, 4], hence forcing students to be physically inside a traditional laboratory. Other learning objectives may be addressed by non-traditional laboratories, i.e. virtual and remote laboratories. The discussion around which type of laboratory (traditional, non-traditional) fits better with each learning objective has already been addressed in previous works [1, 3, 5–6]. The present paper focus on an entirely different, yet relatively unexplored dimension: the sustainability viewpoint. The question addressed is not if traditional laboratories should be replaced by non-traditional ones, based on economic factors, nor what is the optimal formula for combining traditional and non-traditional laboratories in order to attain the best educational results with the lowest investment and maintenance costs. Existent literature has also debated these two aspects, where the conclusions point to a hybrid approach, i.e. non-traditional laboratories complement the training given in traditional laboratories [1–9]. The aforementioned are not meant to replace the last-mentioned ones.

What this paper brings as an original contribution, is the cost associated with certain types of experiments and the savings that can be done by letting students doing more of those experiments in a remote lab (instead of a traditional lab), after guaranteeing a number of conditions and assumptions are met.

The remainder of the paper is organized as follows: section 2 describes the type of experiments and their contextualization in undergraduate engineering curricula; section 3 briefly describes the VISIR remote lab, where those same experiments can be done; section 4 presents the sustainability aspects enabled by VISIR; and, finally, section 5 concludes the paper.

2 EXPERIMENTS WITH ELECTRICAL AND ELECTRONIC CIRCUITS

2.1 A simple contextualization

In the context of this paper, an experiment with an electrical and electronic circuit is understood as any experiment that can be done by first placing electrical and electronic components in a solderless breadboard, then stimulating the circuit with a power Direct Current (DC) supply and/or a function generator, and finally performing measurements with a digital multimeter (DMM) and/or an oscilloscope. These 4 different instruments, plus the solderless breadboard, are usually present in all electronic workbenches, which do not differ much from one engineering school/faculty to another. With this setup, students are able to mount the circuits, using the components made available to them by the teacher, and then perform the experiments, which may involve:

- Applying a specific stimulus and then performing one or more measurements at one (several) specific circuit location(s). For example: (1) student mounts simple circuit with two two-lead components in series (A and B); (2) applies stimulus with a function generator; (3) measures a given physical variable at component A and then measures a 2nd (or 3rd) variable; finally (4), measures the same variable(s) in component B.
- Changing the stimulus and then performing the same measurements. Considering, for instance, a simple sine wave, the student may be asked to change (1) the frequency, (2) the amplitude, or (3) the offset value, and then measure the impact of every change (increment and/or decrement);
- Changing the circuit topology and / or component values and then repeating the same measurement(s).

Typically, students follow a lab script and are expected to produce a report with their measurement results and findings, to be returned to the teacher at the end of the class or at a given deadline (e.g. one week). Fig. 1 depicts this typical scenario, with one student filling in the lab script while observing the measured data, in a traditional laboratory. In this figure, only the DMM is not visible, while the triple DC power supply, the function generator, the oscilloscope and the breadboard, are easily identifiable. Also visible are the interconnections between the circuit mounted on the breadboard and the test & measurement instruments.

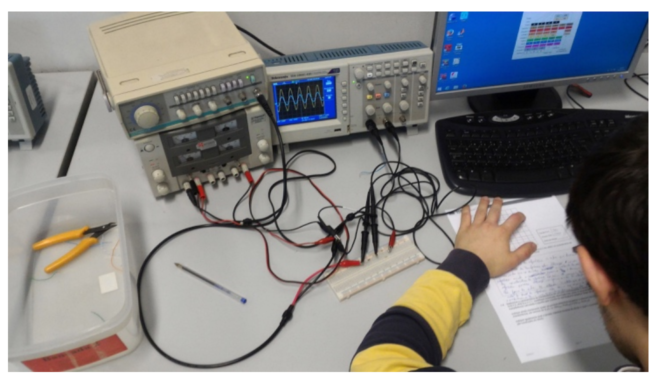

Figure 1: Typical practical class, in a traditional laboratory, for experiments with electrical and electronic circuits.

2.2 Type and scope of the experiments

The type of experiment may change according to the objectives specified in the lab scrip. For instance, if the objective is to simply verify a previously given (simple) physical law, e.g. Ohm's law

$$R = \frac{U}{I} \quad (1)$$

, then the experiment may require performing a large number of measurements to obtain a graph where the relation between the applied stimulus (e.g. U, the voltage applied to a given resistor, with a resistance of x Ω) and the measured variable (e.g. I, the electrical current flowing through the resistor) corresponds to the given law (in this case, a linear equation). The learning objective of this type of experiment usually match that of objective 4 defined in [1], i.e. "***Data Analysis***. *Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions."*

The experiments done with this very simple setup (one input device, one resistor, and one measuring instrument) may then proceed to more advanced levels, e.g. Ohm's law is valid for both DC and Alternate Current (AC), or deviations may be explained by Joule's law, i.e. the current flow produces heat that changes the resistance according to the following equation:

$$R = R_0[1 + \alpha(T - T_0) + \beta(T - T_0)^2 + \cdots] \quad (2)$$

This last sort of experiment may target another learning objective, e.g. objective 2 defined in [1], i.e. "***Models***. *Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.*

Ultimately, teachers may wish to force extreme conditions, for instance asking students to apply a stimulus that will destroy the component handed to them (e.g. fuse the resistor). In such case, teachers may be thinking of objectives 12 or 13 (or a combination of both), i.e. "***Ethics in the Laboratory***. *Behave with highest ethical standards, including reporting information objectively and interacting with integrity.*", or "***Sensory Awareness***. *Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.*", respectively.

2.3 Assessment

Finally, students are usually assessed for what they do in a lab (traditional and non-traditional). This assessment is usually done through indirect observation, e.g. report evaluation, or direct observation of students' performance while doing the experiment (traditional labs), or a combination of both. The assessment can also target group or individual work. One possible scenario could be: a semester with 12 lab classes – students complete a module of 5 lab classes, in workgroups, (each lab class produces a lab report that is assessed by the teacher) and then all students are individually assessed on a subsequent lab class; this sequence is then repeated once [2 * (5 +1) = 12 classes]. In this possible scenario, the practical component may contribute with 50% to the final grade, where each lab report is worth 5 points (max.) and each individual lab assessment is worth 25 points (max.), giving a total maximum of 100 points (then affected by the corresponding percentage of 50%). As a possible example, directly related with electrical circuits, an introductory course on Basic Electricity could have an initial set of experiments, done with resistors, on Ohm's law; series/parallel associations of resistors; Kirchhoff's laws; Joule's law; and Thévenin and Norton's equivalent circuits, all done in the DC domain; followed by a second set of similar experiments done in the AC domain, after an initial characterization of two additional components used in this domain, i.e. coils and capacitors.

3 THE VISIR REMOTE LAB

VISIR is an acronym that stands for "Virtual Instrument Systems in Reality". It is a remote lab for doing experiments with electrical and electronic circuits that offers: (1) a triple DC power supply; (2) a function generator; (3) a DMM; (4) an oscilloscope; and (5) a matrix of stackable boards that allow interconnecting electrical and electronic components, plus the test & measurement instruments. through relays. This matrix effectively emulates a solderless breadboard, thus turning VISIR into a sort of individual lab workbench for every student accessing it.

At the present moment, VISIR is, simultaneously, the recipient of the GOLC (Global Online Laboratory Consortium) award for the "Best Remote-Controlled Laboratory", given for the 1st time in 2015, and the best and most documented remote lab, with more than 100 technical and scientific publications [10–21]. It is installed in Sweden (Karlskrona), where it was developed by Ingvar Gustavsson and his team, back in 1999 [22], and also in Spain (Bilbao and Madrid) Portugal (Porto), Austria (Villach and Vienna), India (Madras), Georgia (Batumi), Morocco (Settat), Argentina (Rosario and Santiago del Estero), Brazil (Araranguá, Florianópolis, and Rio de Janeiro), and Costa Rica (San José).

Fig. 2 displays the main user client interface of VISIR, which represents a virtual breadboard, where students place the components that are made available in the upper area (in a similar way to a practical session done in a traditional lab, where the lab instructors deliver the components to the students) and then wire then together in the virtual breadboard and subsequently connect the circuit to the test & measurement equipment. In physical terms, what happens in the VISIR remote lab, every time a student presses the "Perform experiment" button (right bottom corner of Fig. 2), is: the real components that match the component images available in the virtual breadboard are interconnected in the same way as in the circuit representation, through the matrix relay boards, similar to that illustrated in Fig. 3 (left side). See, in particular the red circles, on both figures, highlighting the component image (Fig. 2) and the real component (Fig. 3). The same matrix relay boards also allow interconnecting the wired circuit to the test & measurement instruments of VISIR, which may be seen on Fig. 3 (right side).

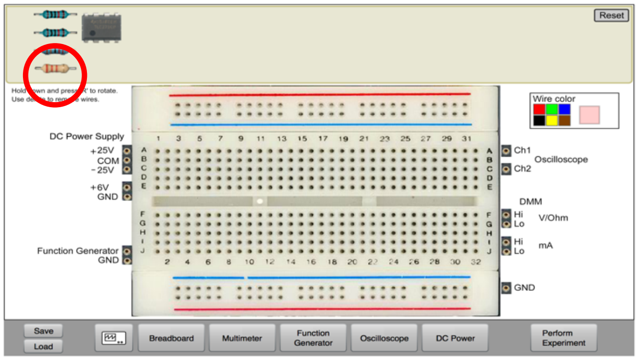

Figure 2: Main user client interface of VISIR, depicting a virtual breadboard. Components are placed in the upper blank area. Access to test & measurement instrument panels is done through buttons placed in bottom area. Experiment is executed every time a user presses the "Perform Experiment" button (right bottom corner).

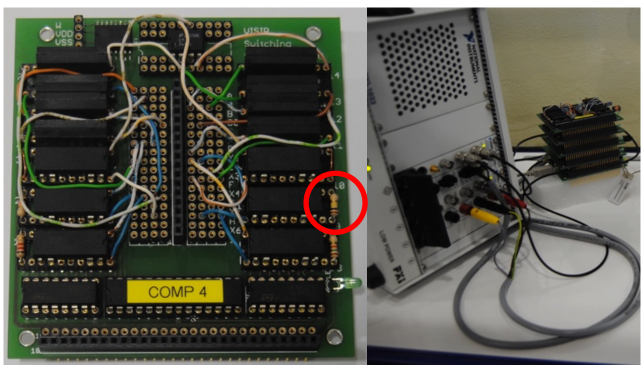

Figure 3: A matrix relay board of VISIR (left) and the test & measurement instruments cased in a PXI-system from National Instruments (right).

One of the most important aspects related to the VISIR remote lab is that it allows using the same components that are used in the traditional lab. The importance derives from the fact the data measured remotely is real and close to that obtained in the traditional lab. In some scenarios that combine calculus, simulations and physical experiments (done locally or remotely), students are sometimes asked to comment on possible differences among the obtained values [23-26]. In this way, VISIR is able to complement a practical class, done in a traditional lab, by allowing the students to continue a given experiment, while obtaining close results.

4 SUSTAINABILITY ASPECTS OF VISIR

4.1 Economic practice

4.1.1 Complementing practical classes. Fig. 4 displays the schedule of a traditional laboratory used for the practical classes (2 hr. each) of a basic electronics course, part of a degree in Electrical and Computer Engineering, delivered at Institution A. This degree is enrolled every year by approximately 150 new students, whereas the course has around 300 students, due to a high failure rate (the course is delivered in the 1st year / 2nd semester). This lab also supports a smaller course with about 7 classes. The laboratory is available from 8:00 a.m. till 11:30 p.m., with the following non-available time periods: (1) Theoretical classes: 8:00 - 9:00 a.m. | 7:00 - 8:00 p.m.; and (2) Dinner: 8:00 - 8:30 p.m. This gives a lab occupancy of approximately 59% (max.) or 70% (considering the non-available periods). The highlighting point is that students are usually not able to use the lab for doing extra work, like preparing beforehand or repeating afterwards a given experiment. There is hardly time left, as clearly visible in depicted figure. Having a 2nd lab always available for such objectives is possible but also very expensive, so the VISIR remote lab emerges as a possible solution, leading to a good economic practice at Higher Education Institutions (HEI).

Figure 4: Schedule of a traditional laboratory serving two courses on electronics (Institution A).

4.1.2 Diminishing equipment under repair. A quite typical problem in lab classes for freshmen is the lack of experience in mounting the circuits and interconnecting them to the test & measuring instruments. This problem is particularly evident to the technical staff serving the laboratories, by the number of blown fuses that are replaced every semester. The authors were able to document this in a previous publication [26] and are reproducing Fig. 5, which clearly provides an idea of the problem. Notice that it is not a question of the price paid for the fuses (almost irrelevant) but the time spent in replacing them and the time the equipment is not available until the fuses are replaced. Again, the VISIR remote lab has been successfully used as a solution to this problem, by having students preparing the experiment in advance, before actually doing it in the traditional lab. Because the interconnections done in the virtual breadboard mimic those that need to be done in the traditional lab, the errors are done in the VISIR remote lab without any sort of damage to the equipment. This is actually one of the advantages associated with remote labs: realistic procedure yet error safe, due to hardware and software protections. As already documented in [27], using VISIR as a sort of pre-chamber to traditional lab classes allowed a 50% reduction in the total number of blown fuses (in a single semester).

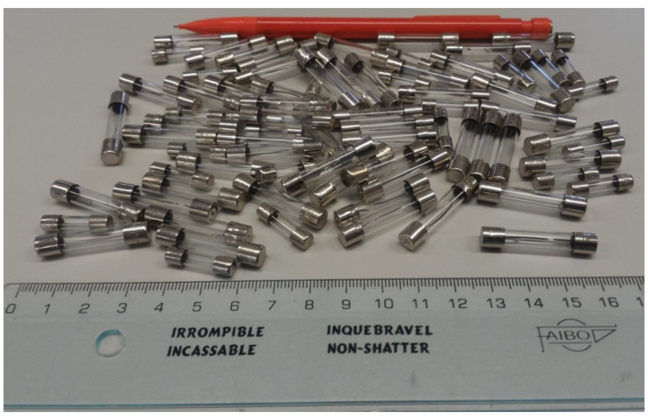

Figure 5: DMM fuses blown at the end of one semester (from one single lab).

4.2 Economic practice and environmental protection

Another problem detected in labs serving courses for freshmen is the number of components that are thrown away every semester. The situation can de described in the following way: students are expected to mount simple circuits and train their psychomotor skills while doing so. The sort of components used for electrical and electronic experiments done in a breadboard is depicted on Fig. 6. They are relatively small and their metal leads, used for interconnecting, tend to break after a limited number of bending actions (usually around 100 times). Fig. 7 depicts some examples of this. Students are expected to mount the circuit, do the experiment and then dismount the circuit, so that students of the following class may start from scratch. Because there is no time to adequately separate the components and store then correctly, many times new components are used from one class to the following one. At the end of the semester, again due to lack of time, the mesh of used components is just garbage, as depicted in Fig. 8. On the opposite side, the components placed in the VISIR matrix relay boards are normally used in thousands of experiments. One particular figure, extracted from Gustavo Alves et al. [19], indicates one resistor to have been used in more than 1,000,000 experiments. So, some basic calculations, indicate that savings regarding one simple component can be in the order of a few hundreds of euros, i.e.:

$$\text{cost of one resistor (orders 250+)} = € \, 0.03 \tag{3}$$

$$1{,}000{,}000 \text{ times} \,/\, 100 \text{ times} = 10{,}000 \tag{4}$$

$$10{,}000 * € \, 0.03 = € \, 300.00 \tag{5}$$

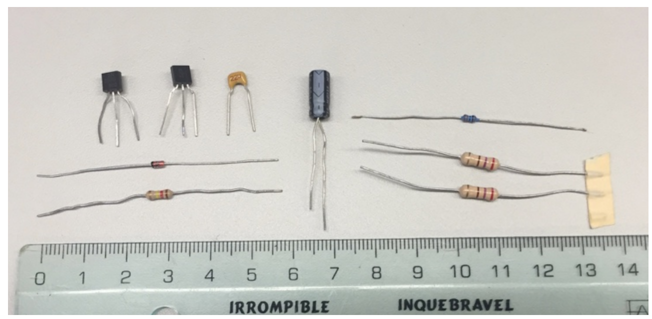

Figure 6: Examples of components used in experiments with electrical and electronic circuits (e.g. capacitors, resistors, etc.)

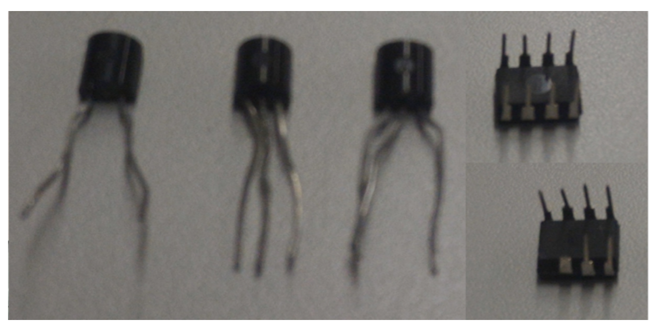

Figure 7: Damaged electronic components due to broken leads.

This sort of situation is also noticeable in individual lab assessment classes, where students feel some additional pressure. In one particular assessment, students are expected to mount a simple circuit with an operational amplifier (OpAmp – see left side of Fig. 7), and then perform some measurements. The 2 hours class is divided into two slots of 55 minutes, each serving 10 students (the lab has 10 fully equipped electronic workbenches and the class is limited to 20 students). Given the tight interval between the two assessment slots and the possibility students may damage the components given to them, two sets of new components are usually prepared for each class, plus some additional spares in case the student detects he/she has damaged some component(s), in the course of the experiment, and asks for a spare one. A simple inspection test made after an individual lab assessment class revealed a percentage of 30% damaged OpAmps. This means that at the end of one single class approximately € 4.00 were thrown into the trash bin (each OpAmp costs around € 0.40 and the total number of damaged components was 10). Considering 16 classes, this gives a total cost of € 64.00 just for one assessment activity of one single course.

Figure 8: Components used in the lab after one single semester. Destination: trash bin!

Regarding the case on how VISIR can be used to help solving the problem, again the answer is: "practice in advance". In fact, many of the errors done by the students when doing the experiment with an OpAmp are related to wrong connections, i.e. connecting the triple DC power supply to the OpAmp in the wrong way. The OpAmp requires a positive and negative voltage plus a reference, i.e. it is not a simple two-lead (positive and negative) connection. Doing this sort of mistakes in VISIR produces an error message that prompts the student to corrective actions, hence reinforcing knowledge acquisition and retention.

4.3 Social integration

Finally, the VISIR remote lab also contributes to the 3rd dimension of sustainable development, i.e. social integration, in the following ways:

- Being a remote lab, it promotes social integration by allowing anyone to access it and do experiments without any sort of time restrictions.
- It is also accessible from smartphones, thus closing the gap between the tech savvy student generations and the more traditional HEI.
- VISIR is also used in secondary schools plus other initiatives for attracting students into Science, Technology, Engineering and Maths (STEM) careers. In this way, VISIR is supporting a better STEM education.

5 CONCLUSIONS

In summary, the present paper addresses the contributions of the VISIR remote lab in the perspective of the three sustainable development dimensions, i.e. economic practice, environmental protection and social integration. The main point is that, once more, VISIR, as any other remote lab, is not meant to replace but rather to complement traditional laboratories, by letting students do more experiments (in the particular case of VISIR, with electrical and electronic circuits) in a sustainable way.

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