An Alternative Way of Teaching Operational Amplifiers Using a Reconfigurable and Expandable Kit

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Abstract—**Early on, students must develop competences by implementing simple or complex electronic circuits with Operational Amplifiers (OpAmps). Traditionally, these skills were mainly developed in laboratory classes, but technology allows us to explore other and complementary ways of aiding students in this achievement. This paper presents a contribution to improve the way OpAmps are included in electronic engineering courses' curricula. A reconfigurable and expandable kit to teach electronic circuits based on the OpAmp uA741 was designed and implemented. This kit comprises a software application locally interfaced with a hardware platform capable of running in a PC. This platform includes a circuit with the OpAmp uA741 able to reconfigure according to a set of parameters defined by a software application. Its reconfiguration capability also enables the establishment of automatic connections for measuring and for applying signals to a reconfigured circuit, plus the ability to simulate the same or other OpAmp-based circuits. This paper provides an overview about the OpAmp uA741 and its relevance in engineering education. After presenting the kit and make some considerations for its improvement, at the end a brief discussion about its implementation in education according to specific educational strategies and methodologies are provided.**

Index Terms—**OpAmps, electronic reconfiguration, simulation, engineering education, e-learning, PBL, flipped-classroom.**

I. Introduction

IN THE literature there are several methods to teach electronic engineering, most of them focusing on caching students' motivation to learn [1], [2]. Videos demonstrating phenomena, plus free and web accessible interactive simulators, are just some of the learning objects that are being applied in education, with successful and promising results [3]. This is particularly important for teaching electronics, and in particular electronic sensors, since most of them are essentially analog, which requires well-designed educational tools. Although the experience shows digital processing has advantageous towards analog processing, such as more accuracy and

versatilely to change the behavior of a circuit, the key point is that the signal processing part of a sensor always requires analogue to digital conversions. It is therefore required a previous processing of the analog signals, even if they are latter converted to the digital domain. Joining this evidence with the required versatility to design electronic circuits, in which concerns the ability to change their behavior without replacing the adopted components, contributed to the appearance of reconfigurable analog devices such as Field-Programmable Analog Arrays (FPAA)[1] and Programmable System-on-Chips (PSoC).[2] The tendency for their wide adoption in the design of analogue electronic circuits may have important implications in the teaching strategy, as referred in [4]. Although, whatever the adopted device for designing analogue circuits, internally they provide the use of one or more Operational Amplifiers (OpAmps), indicating that this type of Integrated Circuits (IC) is still one of the most important for the design of electronic circuits. It is therefore important to understand the best way to teach them according to the best educational methods.

Teaching and learning electronics cannot be limited to teacher-centered methods supported by traditional classroom environments. New strategies are being applied to catch students' interest and to incentivize their autonomy to learn electronics, such as the Flipped-classroom. This strategy is basically a type of blended learning that reverses the traditional learning environment by delivering or providing instructional content outside of the classroom, with good results in electronics engineering [5], [6]. The new and advanced learning objects supported by the Flipped-classroom strategy, which may include distance-learning approaches, have been incentivizing the adoption of the Problem Based Learning (PBL) methodology that defends students' autonomy to solve problems with teacher guidance. Recent studies indicate this methodology with active-learning, experiment-based and project-based learning approaches, a success to teach electronics [7], [8], being therefore important to teach and learn

[1]A Field-Programmable Analog Array (FPAA) is an integrated device containing configurable analog blocks. (e.g. of a well-known manufacturer: http://www.anadigm.com/fpaa.asp)

[2]Programmable System-on-Chip (PSoC) is a family of microcontroller integrated circuits by Cypress (http://www.cypress.com/products/psoc-creator-integrated-design-environment-ide). These chips include a CPU core and mixed-signal arrays of configurable integrated analog and digital peripherals.

OpAmps, which are traditionally the first IC considered in every electronic engineering course. OpAmps simplicity and utility to design simple and/or complex electronic circuits, and their adoption in recent electronic devices, such as the indicated FPAAs and PSoC, justifies, as already referred, their relevance in electronic engineering, which means that students should acquire good knowledge of their operation. Their adoption in many electronic devices and circuits, justifies that all electronic engineering courses include the study of these type of IC in their curricula. Understanding how they work and their common applications are therefore fundamental, requiring the access to good and well-designed educational resources to incentivize the adoption of new educational strategies and methodologies. Regardless of the adopted strategies or methods, educational researchers agree that the experimental activity is fundamental in engineering [9]–[11], and therefore imperative in electronic engineering courses, and in particular to teach and learn OpAmps. Traditionally, educational methods based on theoretical, practical and experimental activates are adopted. While the first two activities are easily included in any course, since the only requirement is the availability of educational contents based on documentation or simulations, the experimental activities can become more difficult to include. The time constrains in a curriculum to conduct a particular experiment, the lack of budget to acquire components and the reduced resources to setup circuits, are only some of the possible difficulties teachers and students may face in electronic courses.

Despite the enumerated difficulties, a solution based on a traditional laboratory is very common, but most of the time students must simulate the circuits using commercial software and setting up those circuits in a breadboard. There are many available software to simulate electronic circuits (e.g. Multisim, Spice, etc.), but some of them require licenses, with the inherent expenses, and setting up a circuit in a breadboard may become time consuming and cause some difficulties to students, due to badly applied connections, noises that may appear, among others. While in some situations setting up a circuit and expose students to those difficulties are part of the learning outcomes, in many situations the main outcome focus on the behavior of the circuit itself, based on the redefinition of some components and parameters. Therefore, this paper presents a reconfigurable and expansible electronic kit able to be reconfigured with different electronic circuits based on a single uA741 OpAmp. Currently it is locally accessed and reconfigured through a computer. It includes a tool to simulate some basic and typical circuits with the OpAmp, and enables the implementation of those circuits using real hardware, as in a traditional laboratory. The integration of a simulation tool together with the experimentation capability is one of the key features of the presented kit.

This paper is an improved extension of a paper published in the conference TAEE 2018 [12]. It presents a more detailed statistical analysis of answers given by teachers and specialists in electronics about the usefulness of the kit in engineering education, and provides some considerations about its adoption using educational strategies and methodologies known as PBL and Flipped-Classroom. Besides this introductory section,

the paper is divided in 6 other sections. Section II contextualize OpAmps in electronic engineering, presenting their main characteristics, plus some current educational platforms. Section III describes the developed kit, presenting its features and characteristics. Supported by the functionalities provided by the kit and in the current trends of engineering education, section IV suggests some improvements to the kit while section V presents and comments some opinions acquired from a group of teachers and specialists in electronics. Before conclusions, section VI sets out considerations to use the kit according to distinct educational strategies.

II. OpAmps in Electronic Engineering

A. Background History

According to the literature [13], in 1943 an American engineer named Loebe Julie created the first operational amplifier circuit. Its origins begins back to the vacuum tube era by the creation of the two-element tube-based rectifier invented by JA.A Fleming in 1904. This vacuum device was characterized by allowing the flow of current in one single direction, performing a rectification function as in the current diodes. Two years later, in 1906, Lee De Forest improved that vacuum device inventing the three-element triode vacuum tube that enabled the control and the amplification of the current, like in the actual bipolar transistors. It was supported by these two vacuum elements that late in 1920's and early in 30's born the first feedback amplifier in the Bell Telephone Laboratories (Bell Labs), leading, in 1940's, to the first tube OpAmps, a general-purpose form of feedback amplifiers using vacuum tubes. Due to their huge size, power consumption, and bulky, in 1950's and 1960's they began to be replaced by miniaturized solid state OpAmps, ending with the first IC OpAmp, as we know it today. The first OpAmp was created at the ends of 60's by the Fairchaild company with the model uA709 being latter replaced by the well-known uA741. These are both constructed based in bipolar transistors, but more recent OpAmps using FET and CMOS technologies can be found in the market with better performances (e.g. LTC6268,[3] LTC6244,[4] LTC1052[5]), such as less power consumption, higher dynamic responses, and reliability. Despite this evolution, the uA741 is still probably the most adopted in engineering courses to teach the basics of OpAmps, essentially due to its good reliability and low prices compared to others.[6]

B. Characteristics and Common Applications

Although the inherent differences among the different models of OpAmps, all are classified as linear devices internally

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[3]The LTC® 6268/LTC6269 is a single/dual 500MHz FET-input operational amplifier with extremely low input bias current and low input capacitance.

[4]The LTC6244 is a dual high speed, unity-gain stable CMOS op amp that features a 50MHz gain bandwidth, 40V/μs slew rate, 1pA of input bias current, low input capacitance and rail-to-rail output swing.

[5]The LTC®1052 and LTC7652 are low noise zero-drift op amps manufactured using Linear Technology's enhanced LTCMOS silicon gate process. Chopper-stabilization constantly corrects offset voltage errors.

[6]Per example the LTC6268 model is about 10 times more expensive than the uA714. After a brief web search the price of the LTC6268 was about 5€ and the uA741 about 0.50 €.
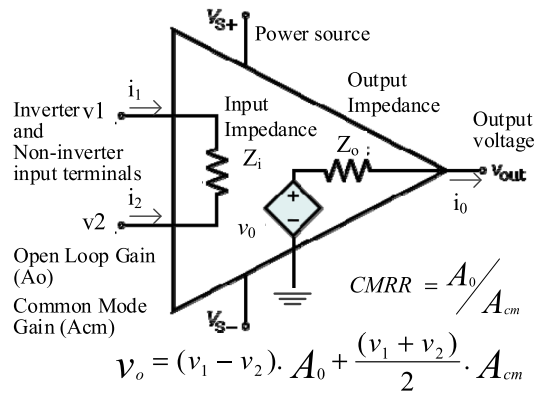
Fig. 1. General schematic of uA741 OpAmp and some mathematical relations.

Reconfigurable	OpAmp Circuit Trainer: Ohm Technologies http://www.ohmtechnologiees.com/lab-trainer-kits.html
	OpAmp Training Kit: Delta Technologies http://www.deltatechnologies.co.in/op-amp-training-kit.htm
	Basic Operational Amplifier: Acumen Labware http://www.acumenlabware.com/electronics-training-kits/basic-operational-amplifier.html
	OpAmp Trainer Kit: Batra Trading Company http://www.btcinstrument.com/electronics-characteristics-curve-apparatus.html
PCB-based	LM741 OpAmp IC with Development PCB Kit: NightFire http://vakits.com/op-amp-ic-development-design-kit-lm741
	Voltage follower Operational Amplifier (buffer) kit: EID http://www.eidusa.com/Electronics_Kits_OP_AMP_BUFFER_1.htm

comprising several semiconductors, resistors and/or capacitors. Commonly used together with other external components, such as resistors, transistors, diodes, capacitors, inductances, or others, their electrical characteristics facilitate the implementation of simple or complex circuits. They allow the establishment of linear or nonlinear mathematical relations to create different types of circuits, such as amplifiers, filters, limiters, etc.

Some of the most important characteristics of an OpAmp are the high voltage gain and input impedance, the low output impedance, as well as a Common Mode gain (Acm), commonly specified by the denominated Common-Mode Rejection Ratio (CMRR), which represents the ability of the device to reject common-mode signals. This IC allows the establishment of particular mathematic relations between the input and output voltages. The generic circuit that represents an OpAmp constructed based on bipolar technology and some important relations are illustrated in fig. 1.

Therefore, supported on these characteristics, the use of OpAmps facilitates the implementation of many electronic circuits that would be much more complex and less accurate to implement if only discrete components were adopted. Nevertheless, implementing circuits with OpAmps requires the use of those components to design circuits, most of them following closed loop designs. The most commonly taught in electronic courses are the inverter and non-inverter amplifiers, integrators and differentiators circuits, since they are the basic circuits whose comprehension allow the implementation of more complex electronic circuit (e.g. filters).

C. OpAmps in Education

Despite the available simulators that adopt OpAmp models to simulate circuits, the inherent complexity of OpAmps and the environment conditions where they operate may create unexpected behaviors not considered in every well designed software simulator. Therefore, it is very common to teach OpAmps not only using the traditional presentation in class-rooms, doing pen & paper exercises sometimes complemented with simulations, but also provide experimental activities to students, so they may understand that simulating sometimes do not provide the same results as a real experimentation. The awareness to the inherent difficulties that real implementations

may pose should be transmitted to every engineering student, and the design of electronic circuits using real equipment is therefore fundamental in every well design engineering course. This educational requirement justifies the existence of several kits with OpAmps available on the market, in order to facilitate, motivate and increase students' autonomy. The kits available in the market to create electronic circuits supported by OpAmps can be grouped in: i) reconfigurable kits, that basically facilitate setting up circuits by changing or controlling the components' values, and ii) PCB-based kits to easy setting up circuits with OpAmps. Table I provides a list of some kits, and shows two examples. Despite the learning outcomes focus on teaching the operation of OpAmps, these two groups of kits fulfil different educational needs. It is reasonable to say that using reconfigurable kits facilitates verifying the operation of the OpAmp, while PCB-based kits allow a more direct contact to the component itself. The last basically serves as a guide to facilitate setting up circuits with OpAmps, exposing students to a direct contact with electronic components.

Only a few platforms are exclusively dedicated to teach and learn OpAmps and most of them don't integrate any simulation tool that would allow students to complement experimental and practical activities required in any engineering course. Others, such as the NI-Elvis besides expensive (about 2500 €) require from students the same effort to implement electronic circuits as common laboratory. Another interesting commercial product is the Lab Volt FACET boards,[7] which are commercial systems prepared for education. Their adoption can be considered to teach OpAmps and other electronic circuits, as already reported in [14], but it is a commercial product, with the inherent expenses of acquisition and the impossibility of easily changing its design with many and distinct components, which may limit the versatility that a classical classroom requires.

Therefore, providing good, well-designed and versatile kits at low prices focusing on teaching a particular component, such as an OpAmp, may motivate and facilitate teachers' and students' activities. Additionally, integrating in the same kit a simulation tool and an experimental and reconfigurable

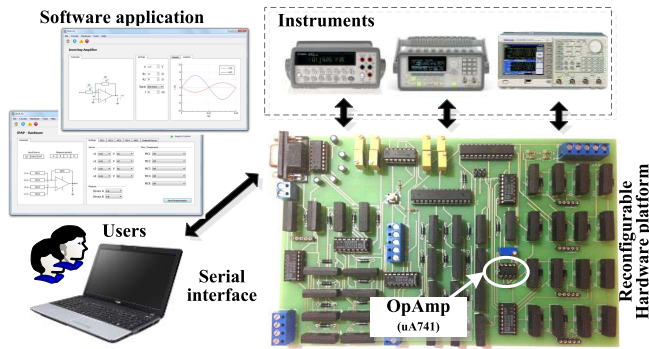[7]https://www.labvolt.com/products/facet-circuit-boards-and-courses

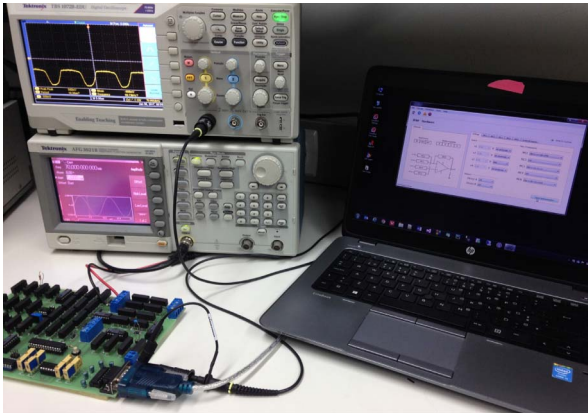Fig. 2. The overall architecture of the implemented kit.

Fig. 3. Picture of the electronic kit exemplifying the use of two external instruments (oscilloscope and function generator).

platform would facilitate the interface between the practical and experimental activities, avoiding this way the use of separated tools. Taking this into consideration, and focusing on teaching and learning OpAmps' operation with design simplicity, it was designed and developed a reconfigurable and expandable kit with the OpAmp uA741 to enable the design and experimentation of different electronic circuits. The kit is controlled by a computer, which enables an automatic replacement of components, and integrates a simulation tool for a previous verification of some of those circuits, as detailed in the next section of this paper.

III. DEVELOPED KIT

The developed kit focus on the simulation, setup and experimentation of electronic circuits based on the OpAmp uA741. It is supported by a local architecture comprising a hardware platform accessed through a software application.

A. Overal Architecture and Functionalities

As represented in the block diagram of fig. 2 and in the picture of fig. 3, the kit comprises a reconfigurable hardware platform interfaced with a common PC through a serial connection. The platform may have external instruments connected to it, and the PC runs a software application to reconfigure the platform and simulate circuits. The platform includes

an OpAmp uA741 implementing a main circuit able to be reconfigured to design circuits to experiment (e.g. inverter circuit and others). The reconfiguration capability provided by the platform is implemented by a set of other electronic components, such as analogue switches, digital resistors, etc.

The platform was designed and developed to enable its expandability. It provides a set of connecting points to integrate other external components in specific branches of a main circuit, which means that the complexity of a reconfigured circuit to experiment may be more or less complex according to those attached components (e.g. resistors, capacitors, other ICs, etc.). By using the software application, it is up to the users to decide the possible circuits to experiment by integrating those external components on the branches of the circuit. To measure or apply some electrical signals in different points of a reconfigured circuit, the platform also enables the connection of external and commercial instruments (e.g. oscilloscope, multimeter, function generator, etc.). Before using the kit the teacher must connect some instruments to particular connecting points of the hardware platform. Later, students should use the software application to place the probes of each instrument in different points of the reconfigured circuit, as they would do when using a breadboard. All connections are automatically made, avoiding errors and facilitating the measurement of some specific signals.

B. Hardware Platform

The main element of the kit is the reconfigurable hardware platform whose main element is the OpAmp uA741 used to form the main circuit that is able to be connected with external components. These components can be grouped in a so-called Module of Components (MC). Additionally, the platform provides 4 other terminals to connect the external instruments to measure or to feed an input terminal of a reconfigured electronic circuit, a RS232 connection to establish the interface to the PC, and a set of terminals to power on the platform. To enable the automatic reconfiguration with distinct electronic circuits using the components provided by the attached MC, the platform has a set of relays (9007-05-00 - Coto Technology) controlled by a μC (ATmega328/P). A digital resistor enables users to control an internal DC power that may source an input terminal of a reconfigured circuit, instead of using an external DC power. Fig. 4 illustrates some of the most important interfaces and components available in the platform.

Thus, the platform is reconfigured with distinct circuits based on the available MC. As represented in fig. 5, users may connect 2 MC to the inverter terminal, 2 MC to the non-inverter and 1 MC to establish a negative feedback loop connection. The components within each MC are selected based on the position of a set of relays. The MC connected to the input terminals forms the MC-n branches and they are controlled by two distinct groups of relays (relays 1 - has 3 relays; and relays 2 - has 4 relays). The MC that creates the negative feedback loop connection forms the MC-F branch and it is controlled by the group relays 2. Each MC can be connected to the platform, and in particular to a branch
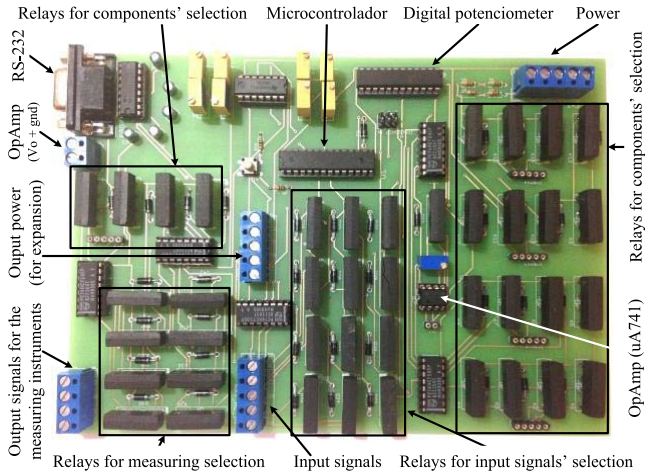
Fig. 4. Photography of the reconfigurable hardware platform with the main interfaces and the internal components.
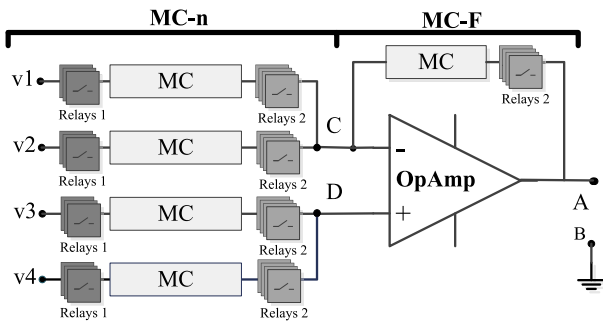

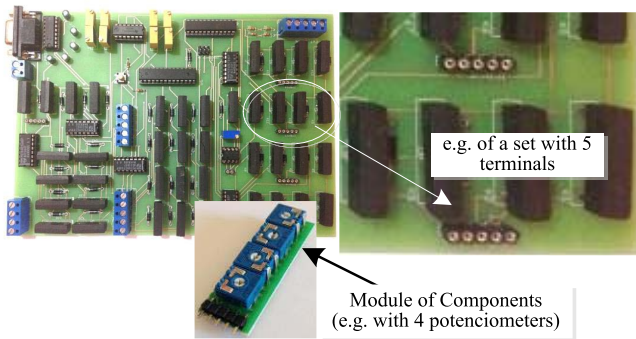Fig. 5. Schematic with the architecture of the reconfigurable main circuit.

Fig. 6. Module of components (MC) used to setup uA741 OpAmp circuits.

of the main circuit, using one of four sets of five terminals, as exemplified in fig. 6. These terminals enable connecting a MC to the inverter or non-inverter terminals, or to establish the negative feedback connection of a traditional OpAmp circuit.

Once a MC is connected to the platform, users may select one component (or subset of components). This selection is made through the indicated relays, turning them on/off. A MC can integrate different type of components. The only requirement is that each module should has 4 input terminals and a common output. Internally it can have resistors, capacitors, or even a specific electronic circuit. It is up to the user
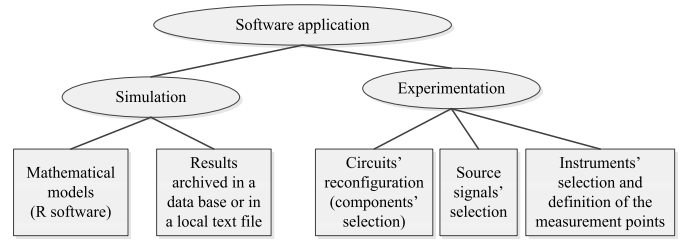

Fig. 7. Functionalities provided by the software application.

(the teacher) to decide what will be the MC provided in the reconfigurable main circuit. To measure particular signals of a reconfigured circuit, users can also place the probes of the selected instruments in particular points of the circuit. For the selection of a particular component or a circuit provided by a MC, and for the selection of each measurement point, users must use the software application, which also enables the simulation of some simple circuits.

C. Functionalities of the Software Application

The software application belongs to the developed kit and, as represented in the diagram of fig. 7, it has two main functionalities for analyzing electronic circuits based on the OpAmp uA741: i) simulation and ii) experimentation.

The simulation of a particular circuit is supported by a set of predefined mathematical models specified using the R software.[8] The obtained results of those simulations can be archived in a database or listed in a comma delimitated text file (*.cvs) for future analysis.

To experiment some (or all) the simulated circuits, the software application allows the reconfiguration of the platform. As indicated, this process involves the components' selection provided by the available MC attached to the platform, and the definition of the source signals attached to the inverter or non-inverter input terminals of the reconfigured circuits. Once defined, users are able to experiment the circuits by specifying the measurement instruments and the location of their probes in particular points of the circuit, also using the software application. The measurements are acquired by common and commercial instruments attached to the platform.

During an experiment, the software application communicates with the platform using the serial interface, by sending commands and receiving replies. The commands send information to the platform for turning on/off a particular relay, for defining a source signal, for specifying the points to place the probes of a particular instrument, etc. In order to facilitate the synchronization between the software application and the platform, the adopted μC, which interprets all commands and generates the associated replies, internally implements a memory divided into different fields that specifies, in each moment, the way the platform was reconfigured with a particular circuit. All the information sent by each command are gathered into this memory so the μC can read it to know the current configuration state of the main circuit.

[8]R is a free software for statistical computing and graphics (https://www.r-project.org/).
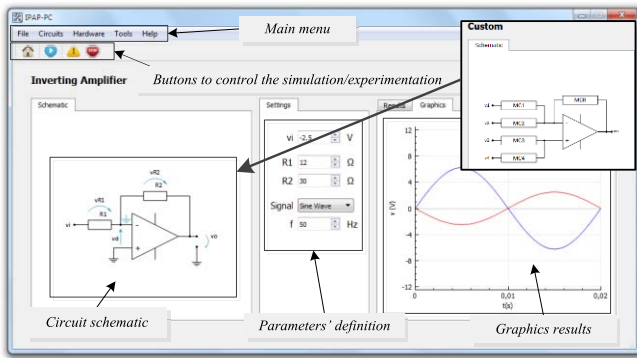
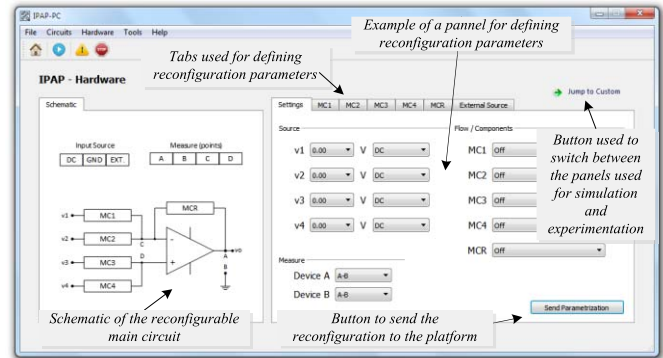Fig. 8. Example of an interface for simulating circuits.

Fig. 9. Interface for reconfiguring and experimenting circuits.

As indicated, for simulating a circuit the software application should has the associated mathematical models defined in R scripts. These scripts do not need any recompilation, since the R software module that is installed in the PC together with the application interprets them. The parameters of the circuit able to simulate and the associated results retrieved from a particular simulation are specified in a XML file format, facilitating this way their presentation in the interface of the software application. For experimenting a circuit, teachers must physically attach the required MC. The students may setup a particular circuit and describe the available components in a XML file (setting.xml), so the software application may read it, and display that information in the interfaces of the software application.
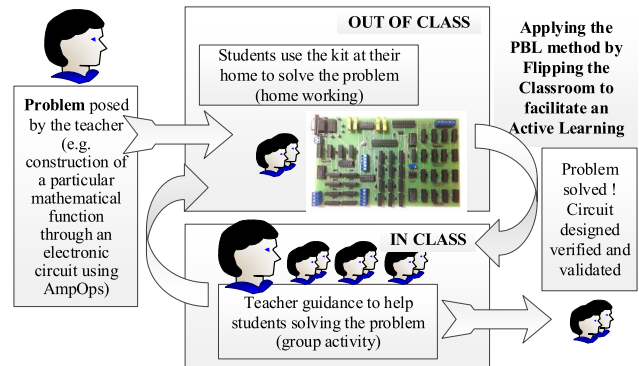
D. Interfaces of the Software Application

The software application, whose main interface is illustrated in fig. 8, includes a set of 4 buttons, a main menu and other interface panels. The set of 4 buttons enables controlling the simulations and the experimentations (run, reset and status, plus a help menu) and the main menu has 4 other submenus, namely:

• File: provides access to R files and enables the selection of other files to save results obtained from simulations (database or comma delimitated text file - *.cvs format -);

• Circuits: Access to the available circuits for simulation;

• Hardware: Access to the platform for reconfiguring and experimenting a circuit;

• Tools: Access to a webcam interface attached to the PC to facilitate users' observation of particular measurements;

• Help: Information about the software application.

The interface panels display the schematic of the circuit to simulate, gives the possibility for users to select parameters of that circuit, and displays the results of the simulation. In the example, an inverter amplifier simulation plus an indication to a custom circuit layout is illustrated. The software application provides several other circuits for simulation, namely the inverter, non-inverter, differential, integrator, comparator, follower, plus a custom circuit. This custom circuit enables users to select different types of circuits according to the provided R modules defined in the software. This means that the software application can be extended with other circuits

Fig. 10. Applying the PBL method by flipping the classroom to design, verify and validate typical OpAmp circuits' designs.

once the mathematical R modules are included (this update is responsibility of a technician or a teacher). Additionally, the custom circuit layout is similar to the available possibilities to reconfigure the platform. This means that after a simulation users can experiment the same circuit using the platform, once the MC attached in the platform are in accordance with the available R modules created for simulation.

Therefore, for running a simulation, users should select the circuits' submenu and chose a particular pre-defined circuit or, the custom circuit. After selecting the circuits' submenu, users have access to the circuit's schematic and to a panel where they can select the values for each component. After running the simulation, they get the results that are presented in a numeric or graphical form. The obtained results can them be save in a database or in a text file, by selecting the File submenu.

For experimenting a particular circuit, users should select the hardware submenu to access the interface illustrated in fig. 9. This interface provides the schematic of the custom circuit that is basically the main circuit with the OpAmp uA741 able to be reconfigured by changing a set of parameters. The components available in the platform and the indication if a specific input is connected to a particular external source are indicated in each of the remaining submenus able to select using different tabs. These submenus are automatically filled when a particular MC or external source are attached to the platform and the XML file (*settings.xml*) is edited.

This task belongs to a technician or to a teacher during the preparation of a particular experiment. For placing the probes of the instruments attached to the platform in the accessible points of the main circuit (A, B, C or D) users should selected the available solutions for each of the devices. Once all parameters and instruments probes' connections are defined, users must send that information to the platform using the button named *send parametrization*. To enable a comparison between simulating and experimenting a circuit, both simulation and experimentation interfaces provides a button to switch between them. Note, however, that not all simulating circuits can be experimented using the platform and vice-versa, since simulating and experimenting requires independent preparation of the kit. While experimenting a circuit requires attaching the MC and defining a particular XML file describing the available components; simulating a circuit requires defining the mathematical R modules. Obviously, in order to allow students to compare simulations with real results obtained through experimentation, it is desirable that a particular circuit can be both simulated and experimented.

IV. PERSPECTIVES FOR ITS ADOPTION IN EDUCATION

Currently the kit offers some advantages for electronic engineering courses. The possibility it offers for students setting up circuits supported by a computer, overcome some problems that they may arise if a traditional breadboard was adopted. By using a circuit, able to be reconfigured and/or parametrized with different components, overcome possible bad connections between components caused by human mistakes or broken wires that are traditionally difficult to detect. This approach may limit a relevant learning outcome that is the importance of exposing students to possible problems that may arise when setting up a circuit using a breadboard. Nonetheless, it facilitates the design and the experimentation of a particular circuit.

The use of this kit in a real educational context must therefore be evaluated concerning the learning outcomes. The facility the kit provides to setup circuits should be considered for situations where the main educational goal focus essentially in the behavior of the circuit it-self. The problems that traditionally a student face when setting up an electronic circuit should not be the focus of its learning. Additionally, with this type of kit, teachers may easily include the experimental activity of any laboratory, since the time required for a student to setup an electronic circuit with an OpAmp is drastically reduced. They are able to faster and easy the validation of theories and calculations previously made. They do not need to be concerned picking up components and setting up the circuit, activities that are traditionally very time consuming and in many situations are not the focus of the learning outcome.

It is also important to emphasize the possibility this kit offers for students to simulate circuits before experimenting them with real components. With current kit students don't need to use external simulators that can bring some disadvantages such as; some of them are not free, others requires a previous installation of several software applications and tools,

and others requires a web access to use them, which would demand an internet connection that, in some situations, can be inaccessible.

Another relevant issue of the kit is its expandability. It provides the possibility of adding complex and/or simple external MC in some branches of the main circuit. Teachers may provide those MC to students, or insert them in the kit, expanding, this way, the possible circuits to be experimented without the necessity to ask students to setup the circuit by their own, as they usually do using a traditional breadboard.

Despite the flexibility, current version provides to reconfigure and expand OpAmp-based circuits, it has some limitations that are important to consider for future improvements. Currently it is impossible to implement positive loops, and it is difficult to design circuits requiring complex branches (e.g. the well-known Sallen-Key Lowpass Filter circuit would require many external connections). Moreover, currently the kit only allows a local simulation / experimentation. Its application in a traditional laboratory class would require that each individual or group of students have one of these kits. Although it would facilitate simulating circuits without any commercial software, and setting up the circuits with real components, the associated costs to have several kits available in a laboratory can be prohibitive. This means that its adoption in a traditional laboratory is not possible if costs are a mean concern. Therefore, to overcome cost problems, the remote access to the kit as a remote laboratory is a solution to consider in future developments. Once the kit is PC-controlled, its remote access is a natural evolution, which has been seen as an added value to improve students learning outcomes in engineering education as a complement to the hands-on and simulated laboratories [15], [16].

The access to the hardware platform can be implemented according to two accessing modes, namely i) synchronous or asynchronous. In the synchronous mode a time slot is reserved when a student is accessing the platform. In the asynchronous mode students may use the platform whenever they want, defining the configurations and acquiring results. A publication describing a solution for experimenting electronic circuits using an asynchronous mode was already published [17], but its appliance in education had no continuity. A typical and well tested remote laboratory that uses this accessing mode is the VISIR system [18]. It is currently well accepted by the educational community [19], [20] and is being adopted in several European institutions (Portugal, Spain, Sweden, etc.). Additionally, an ERASMUS+ project, named VISIR +, widespread their adoption in Latin American countries by integrating it as an important leaning object of common electronic engineering courses [21], [22]. However, and despite the maturity of the VISIR system, that makes it as a solution in education, it is not exclusively dedicated to experiment OpAmp circuits, neither it has a simulation tool, that would facilitate the integration of the practical and the experimental activities in a single educational tool. Furthermore, it is an expensive system (it can cost about 20.000 €) and it requires users to setup a circuit using a virtual breadboard, which could not be a learning outcome. Despite current kit can be applied in an engineering course given support to the experimental

lessons, the remote access is an important improvement to take into consideration in future releases, since it will reduce the associates costs that would exist if several kits were required to conduct an experimental lesson.

Although the considerations presented in this section are supported in authors' opinions, it was decided to get other researchers and teachers' opinions about the kit and its relevance to electric engineering education, namely to teach uA741-based electronic circuits.

V. TEACHERS' PERCEPTION FOR USING THE KIT

To better understand the educational relevance of the described kit in electronic engineering, and its possible didactical implementation, the kit was demonstrated in a technical session to a group of teachers and specialists [23].

During the demonstration some simple circuits with the OpAmp were prepared, namely the inverter and non-inverter circuits, one integrator and one differentiator. Placed in a specific workbench, participants had the opportunity to see the operation of different circuits configured in the kit. After the demonstration and discussion of its purposes and characteristics, where participants shared their thoughts and discuss their doubts, they were asked to fulfil a questionnaire, addressing their view about its educational value, possible learning facilitators and their potential interest in using this tool. This questionnaire, whose responses are presented in table II, was mainly divided in 3 parts: Part I to understand the participants' background; part II to evaluate their perception about its educational value, and part III to appraise their receptiveness in adopting this kit in their classes. This questionnaire was previously presented to three teacher-researchers in the area who validated its use after discussing its relevance and clarity of the questions towards its objectives. Despite the short number of participants (10 participants), they represented an aleatory group, from different universities and countries. All are active researchers in the area, and some have many years of expertise teaching electronics. So, in this study their opinions were considered representative towards the assessment of the educational value this tool may represent.

Generically observing the plain results presented in the table II, it is evident that the kit triggered interest to the participants, since the large majority indicated that they would like to use the kit in their classes, even if they are not currently teaching the thematic. In this context, also note that the remote access is a requirement for two of the participants to use the kit, while all the others do not pose any constrains using it like it is (with a local access).

It is noteworthy that teachers with more years of expertise find this tool more useful for supporting students in their learning – a positive correlation is found between these two variables (Spearman's Rank correlation, $p = 0,043$). The fact of teaching (or not) these contents, do not appear to influence their perception, but their experience with similar tools does. In fact, the support for students learning have different kind of perception by teachers who have already teach with similar tools than those that did not (Chi-square test, $p = 0,014$). It is also interesting to note that participants

TABLE II

QUIZ ABOUT TEACHER'S PERCEPTION USING THE KIT IN EDUCATION

Participant #:	1	2	3	4	5	6	7	8	9	10
Years of expertise in the area	1	18	6	20	2	2	26	11	25	5
Did you teach the contents supported by the educational kit ?	Y	Y	N	N	N	N	Y	Y	Y	Y
If yes: Is it usual doing laboratorial experiments with the students about the thematic supported by the kit?	Y	Y						Y	Y	Y	Y
If yes: Did you already use similar tools in your classes?	N	N					Y*7	Y*8	Y	N
If you adopt this kit in the classes (select the best options):										
What would be the benefits?										
i. Contribution to consolidate the knowledge in the thematic.	✓		✓						✓	✓
ii. Contribution to integrate the knowledge						✓				✓
iii. Contribution to contextualize the theoretical part of classes.	✓			✓	✓		✓			✓
iv. Promote experimental competences.				✓	✓		✓	✓	✓	✓
v. Support students during their learning.							✓	✓	✓	
vi. Reduce the required time to explore the thematic.								✓		
vii. Improve the teaching methodologies.	✓						✓	✓		✓	✓
viii. Expand the adopted resources.		✓								✓
ix. Improve the students' motivation and enthusiasm.						✓				✓
What difficulties do you preview?	*1									
i. Lack of time.				✓						
ii. Lack of technical means.						✓		✓	✓	
iii. Lack of effort by the students.		✓	✓	✓						
iv. Lack of colleagues' support.						✓		✓		
v. Lack of relevance for the learning outcomes.										
vi. Lack of know-how facing problems or students' feedback.						✓			✓	Y
Would you like to have this resource available to support your classes?	Y	Y	N	Y	Y	Y	Y	N	Y	Y
…. and if it was remotely accessible?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

*1 – "Had to implement a couple of circuits";
*7 – "Oscilloscope, wave-generator, bread-board circuits"
*8 – "Custom design"

selected many relevant benefits for using the kit in education, in particular the promotion of experimental competences to the users (students), and most of them see its adoption as a contribution to contextualize the theoretical part of classes. It was found a correlation (Spearman's Rank correlation, $p = 0,009$) between the group of answers to the perception of the kit benefits to teach, and the group of answers related to the perception for students learning advantages. This indicates that teachers found this tool useful for their teaching practice and for the students learning. Another curious result is that the more teachers identified constrains in using this kit, the more they think it would be helpful for student's promotion of experimental competences (Spearman's Rank correlation, $p = 0,046$). This particular result may indicate that teachers are aware for the difficulties and for the importance of putting in practice new methodologies and new resources in education. Particular difficulties for using the kit were not identified with a clear unanimity. The lack of effort by student, lack of technical means and lack of know-how facing problems or students' feedback, were pointed out as the most probable ones. Complementing our analysis with the informal comments participants made during the presentation, indicates that from the teachers' point of view, the kit would be interesting but it would require a previous presentation to students, so they can understand the versatility it offers to simplify and easy the design of electronic circuits based on the uA741. Additionally, according to the obtained comments it is reasonable to say that teachers see the technical support to use the kit as fundamental, in order to overcome possible problems that may occur. It is also interesting to note that the constraints to teach using the kit do not affected the will teachers have to use it (no relation was found).

At the end, and by unanimity, all participants indicate that a remote access to the kit would incentivize its adoption,

despite most of them had already indicated their interest using it in their classes. These results justified and incentivized some improvements to the kit, in particular the development of the remote access. In parallel, addressing some of the teachers concerns and high values of the tool, a didactical implementation can be latter designed for a real educational scenario, which can follow the PBL methodology and the Flipped-classroom strategy.

VI. Adoption in Education

Based on results and suggestions, the idea of transforming this kit into a didactical implementation was consolidated. This can be accomplished using different methodologies, as an educational module or a resource to complement traditional teaching and learning methods applied in electronic engineering courses [24]. This kit simplifies the way OpAmp circuits can be setup, since students do not need to hand wire components. By reducing the possibility of making bad connections, which could disperse students' attention from the main goal, students may focus particularly on the circuit understanding. By simplifying the process of setting up circuits, students' autonomy is increased and so is their active learning process, which may also lead to students gain in motivation towards the experimental work.

This kit can also be an important resource to use in traditional and teacher centered theoretical classes. Currently, the time curricula of electronic engineering courses allot to explore all-important OpAmp circuits is lower than it would be desired. It is very common that most of the circuits are theoretical presented without any verification or validation, which lead that in most of the time students do not give the required importance to some theoretical issues. By using this kit teachers have an additional resource to use it in their classes. Besides theoretically presenting OpAmp circuits together with the mathematical analyses of their behavior, they can demonstrate their real operation. Like students, they can simulate and setup distinct circuits without wiring the components, demonstrating their operation and the differences between reality and simulation. In fact, the kit also provides teachers with the possibility to show the importance of a real verification of the circuits, instead of just simulating them. Since the kit provides both possibilities, simulation and experimentation, teachers may use this facility to emphasize the importance of the real experimentation. The usual differences between simulating and experimenting a circuit is, by their own, a motivational aspect that will encourage students. It is most common students distrust some simulations whose results are not in accordance with previous calculations. If differences between a circuit mathematical analysis and simulation exists, students tend to pinpoint the problems to the simulation software, even if it is a well-tested product. With the presented kit, this mistrust can easily be overcome. Students have both possibilities in the same kit, allowing them to verify and validate the OpAmp circuit under analysis.

On the other hand, acting as a complementary resource to the educational process used to teach and learn OpAmps, it can be seen as an important resource to implement methodologies like the PBL where, through teacher guidance, students must develop competences while solving particular problems on their own. Providing a resource like the described kit would facilitate students' activities. They do not need to go to a typical laboratory to setup an OpAmp circuit that they have idealized to solve a particular problem. Instead, in their homes, using a traditional computer connected to the kit, students would be able to simulate, implement and test real circuits. They also do not need to request particular components to run a real circuit, therefore simplifying the way they may solve the problems posed by their teacher. Additionally, students would gain the incentive to verify and validate the correct operation of other OpAmp circuits usually presented during a course.

This educational resource can also facilitate the implementation of a Flipped-classroom strategy to teach and learn OpAmp circuits. It can contribute to shift the traditional teaching and learning process, by previously providing students with the access to the designated contents and then use the classroom to explore the kit, develop practical knowledge and consolidate their learning. This implies a shift from a typically teacher-centered, to a student-centered model in which the time in the classroom or laboratory explores topics in greater depth and create meaningful learning opportunities.

Through any of these methodologies (or strategies), each student or group of students may use the kit to solve teacher proposed problems at their own pace, from anywhere, at any time, and use the traditional laboratory or class to discuss the encountered solutions. These advantages are already been established in literature as being facilitators of students' learning [24], [25]. It is then predictable that students may increase their engagement in the learning process, since they will be able to solve the problems on their own, seeking the professor when and only when they already thought about the problem. Through this process students will construct and consolidate their knowledge. Moreover, during the discussions made in the classroom and/or laboratory they have the possibility to show their solutions which for sure will motivate their learning and promote a healthy competitive learning.

The use of the kit in education can be summarized through figure 10. A possible example is a typical signal conditioning circuit problem. Supposing that a particular mathematical function is required to be implemented through an OpAmp circuit. This can be a problem proposed by the teacher that must be solved by students using the kit at their home to verify and validate possible circuit solutions. Through this process, a set of class meetings can be scheduled with the teacher to tutor students through the process of solving the problem under analysis. In class and out of class interaction can be repeated several times until a final solution can be found. This type of interaction is a typical adoption of Flipped-classroom strategy to solve a problem supported by the use of the PBL methodology. It is therefore predictable that the active-learning, experiment-based and project-based learning approaches, will be promoted and therefore a motivation for the involved actors in the teaching and learning process for solving problems based on OpAmp circuits.

VII. Conclusion

OpAmps are probably the most known IC in electronic engineering. The simplicity they provide for designing electronic circuits (amplifiers, filters, limiters, etc...) justifies their wide adoption, and the requirement to teach and learn them in every electronic engineering course. As any other engineering thematic, teaching and learning OpAmps requires a compromise among 3 educational activities; the theoretical, practical and experimental. While the first activities are easily included in any curriculum, since they are basically provided by documentation and/or simulations, the experimental activity requires a particular attention, since the pedagogical resources are more difficult to implement and their design and functionalities must be well accepted by students and teachers.

This paper described the design and the implementation of an educational kit to support the teaching and learning of OpAmps. Currently locally accessible by a software application that enables simulating and experimenting real circuits based on the OpAmp uA741, its adoption in a real educational context was not validate yet. Nevertheless, the functionalities and flexibility it provides to simulate and create different circuits based on an OpAmp perspectives its well acceptance in education to support the required experimental component of any curricula, as predicted by some researchers and teachers in the area. Despite some minor technical improvements to the developed kit are still required, one of the most important improvement is to enable its remote access. It is predictable that only with a remote access to the platform the kit could be a real solution to consider in an engineering course. Currently the kit gives some advantages to easy and fast the implementation of electronic circuits without the necessary use of a traditional breadboard, components and wires. If the educational outcome focus on understanding the circuit it-self, the use of the kit is a solution (complementary or not) to a traditional laboratory. However, since it is locally accessed, using it in education would require that each student or group of students should has one kit, which will increase very much the associated expenses (the developed kit had a price of about 300 €, considering components and the PCB). Since the expenses are traditionally a key concern that have been justifying the adoption of different education tools, namely the use of remote laboratories, it is reasonable to say that providing a remote access to this kit, managed by a virtual learning environment such as Moodle, would guarantee its well acceptance and relevance to improve electronic engineering education. Finally, it is reasonable to say that the kit can be an important educational resource for implementing the PBL method using a Flipped- classroom strategy. The kit can be used by students at their homes or in-group meetings to show developments in an easy way, without the necessity of going to traditional laboratories.

Acknowledgment

References

[1] F. Amiel, D. Abboud, and M. Trocan, "A project oriented learning experience for teaching electronics fundamentals," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 98–100, Dec. 2014, doi: 10.1109/MCOM.2014.6979959.

[2] I. Ugarte, V. Fernández, and P. Sánchez, "Motivation of students in the learning of digital electronics through the double integration: Remote/presential work and theoretical/laboratory classes," in *Proc. Technol. Appl. Electron. Teaching (TAEE)*, 2012, pp. 63–67, doi: 10.1109/TAEE.2012.6235408.

[3] A. D. Ritzhaupt, "Learning object systems and strategy: A description and discussion," *Interdiscipl. J. e-Skills Lifelong Learn.*, vol. 6, no. 1, pp. 217–238, 2010, doi: 10.28945/1306.

[4] C. Felgueiras, D. Areias, J. Macedo, A. Fidalgo, and G. Alves, "Reshaping digital methodologies to the analog world," in *Proc. 13th Int. Conf. Remote Eng. Virtual Instrum. (REV)*, 2016, pp. 366–370, doi: 10.1109/REV.2016.7444504.

[5] H. B. Karayaka and R. D. Adams, "A hybrid flipped classroom approach to teaching a power electronics course to electrical engineering students," in *Proc. ASEE Annu. Conf. Expo.*, Seattle, WA, USA, Jun. 2015, pp. 26.58.1–26.58.16, doi: 10.18260/p.23399.

[6] L. Li, "Project-based learning in electronic technology: A case study," *Eur. J. Eng. Educ.*, vol. 40, no. 5, pp. 499–505, 2015, doi: 10.1080/03043797.2014.987650.

[7] J. P. Becker, C. Plumb, and R. A. Revia, "Project circuits in a basic electric circuits course," *IEEE Trans. Educ.*, vol. 57, no. 2, pp. 75–82, May 2014, doi: 10.1109/TE.2013.2273311.

[8] J. P. Mendoza, J. M. V. Carrizo, and F. J. R. Sánchez, "Project based learning experiences for embedded systems design," in *Proc. Technol. Appl. Electron. Teach. (TAEE)*, Seville, Spain, 2016, pp. 1–6, doi: 10.1109/TAEE.2016.7528370.

[9] N. S. Edward, "The role of laboratory work in engineering education: Student and staff perceptions," *Int. J. Electr. Eng. Educ.*, vol. 39, no. 1, pp. 11–19, Jan. 2002, doi: 10.7227/IJEEE.39.1.2.

[10] R. V. Krivickas and J. Krivickas, "Laboratory instruction in engineering education," *Global J. Eng. Educ.*, vol. 11, no. 2, pp. 191–196, 2007.

[11] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, no. 3, p. 7, Sep. 2006, doi: 10.1145/1132960.1132961.

[12] R. Costa, P. Portela, G. Alves, M. C. Felgueiras, and C. Viegas, "A reconfigurable and expandable kit to teach electronic circuits based on operational amplifiers," in *Proc. XIII Technol. Appl. Electron. Teach. Conf. (TAEE)*, 2018, pp. 1–10, doi: 10.1109/TAEE.2018.8476096.

[13] W. G. Jung, "Op amp history," in *Op Amp Applications Handbook*. Burlington, MA, USA: Newnes, 2006, ch. 8, pp. 765–830.

[14] H. Ben, J. Matthew, H. Robynne, and S. Alex, "The old and the new: Student perceived efficacy of electronics laboratory equipment—DRO," in *Proc. 24th Australas. Assoc. Eng. Educ. Conf. (AAEE)*, 2013, pp. 1–12.

[15] B. Balamuralithara and P. C. Woods, "Virtual laboratories in engineering education: The simulation lab and remote lab," *Comput. Appl. Eng. Educ.*, vol. 17, no. 1, pp. 108–118, 2009, doi: 10.1002/cae.20186.

[16] J. R. Brinson, "Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research," *Comput. Educ.*, vol. 87, pp. 218–237, Sep. 2015, doi: 10.1016/j.compedu.2015.07.003.

[17] N. Sousa, G. R. Alves, and M. G. Gericota, "An integrated reusable remote laboratory to complement electronics teaching," *IEEE Trans. Learn. Technol.*, vol. 3, no. 3, pp. 265–271, Jul. 2010, doi: 10.1109/TLT.2009.51.

[18] M. Tawfik *et al.*, "Virtual instrument systems in reality (VISIR) for remote wiring and measurement of electronic circuits on breadboard," *IEEE Trans. Learn. Technol.*, vol. 6, no. 1, pp. 60–72, Jan. 2013, doi: 10.1109/TLT.2012.20.

[19] A. V. Fidalgo *et al.*, "Using remote labs to serve different teacher's needs A case study with VISIR RemotElectLab," in *Proc. 9th Int. Conf. Remote Eng. Virtual Instrum. (REV)*, 2012, pp. 1–6, doi: 10.1109/REV.2012.6293149.

[20] J. Garcia-Zubia *et al.*, "Empirical analysis of the use of the VISIR remote lab in teaching analog electronics," *IEEE Trans. Educ.*, vol. 60, no. 2, pp. 149–156, Oct. 2016, doi: 10.1109/TE.2016.2608790.

[21] M. C. Viegas *et al.*, "The VISIR+ project—Preliminary results of the training actions," in *Proc. Online Eng. Internet Things*, Cham, Switzerland, 2018, pp. 375–391, doi: 10.1007/978-3-319-64352-6_36.

[22] N. Lima *et al.*, "The VISIR+ project-helping contextualize math in an engineering course," in *Proc. 4th Exp. Int. Conf. (EXP)*, 2017, pp. 7–12, doi: 10.1109/EXPAT.2017.7984369.

[23] R. J. Costa, P. Portela, and G. R. Alves, "An educational kit to teach and learn operational amplifiers," in *Proc. 4th Exp. Int. Conf. (EXP)*, Faro, Portugal, 2017, pp. 137–138, doi: 10.1109/EXPAT.2017.7984353.

[24] M. Hernández-de-Menéndez, A. V. Guevara, J. C. T. Martínez, D. H. Alcántara, and R. Morales-Menendez, "Active learning in engineering education. A review of fundamentals, best practices and experiences," *Int. J. Interact. Des. Manuf.*, vol. 13, no. 3, pp. 909–922, Sep. 2019, doi: 10.1007/s12008-019-00557-8.

[25] D. Kanteti, D. V. S. Srikar, and T. K. Ramesh, "Active learning techniques and impacts," in *Proc. 5th IEEE Int. Conf. MOOCs, Innov. Technol. Educ. (MITE)*, Nov. 2017, pp. 131–134, doi: 10.1109/MITE.2017.00029.