Teaching and learning Operational Amplifiers using a reconfigurable and expandable kit

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Abstract - **Operational Amplifiers (OpAmps) are one of the most important integrated circuits in the area of electronics. These type of devices are widely adopted in the area since they allow the design of simple and/or complex analogue circuits without many efforts. It is therefore fundamental to create innovative educational solutions to facilitate their teaching and learning, and in particular the inclusion of more experimental work in a course curricula. For this purpose, it was designed and implemented a reconfigurable and expandable kit to teach and learn electronic circuits based on the OpAmp uA741. The kit comprises a software application and a hardware platform. The software application allows the simulation and the reconfiguration of real electronic circuits based on the OpAmp uA741 included in the hardware platform. For measuring and/or applying signals to a particular reconfigured circuit, users may establish automatic connections. In this paper it is described the features and functionalities provided by the kit, and an overview about the OpAmp uA741. At the end, some teachers' opinions about their perceptions concerning a possible adoption of the kit in a real educational scenario are presented.**

Keywords - OpAmps, Reconfiguration; Simulation, Engineering education, E-learning.

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 that digital processing has advantages 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 are, 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 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

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[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.

the access to good and well-designed educational resources to incentivize the adoption of new educational strategies and methods. Regardless of the adopted strategies or methods, educational researchers agree that the experimental activity is fundamental in engineering [9][10][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 in some situations can become more difficult to include. Time constrains in a curriculum to conduct a particular experiment and the lack budget to acquire components and resources to setup circuits, are only some of the possible difficulties teachers and students may face in any electronic course.

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 renewed version of a paper already published in the TAEE2018 conference [12]. Besides this introductory section I, it is divided in 5 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 some by the current functionalities provided by the kit and in the current trends of engineering education, section IV suggests some improvements to the kit and perspectives authors' opinions about its adoption in a real educational scenario. Before the conclusions presented in section VI, section V provides some teachers' perceptions about using the kit in education, supported by a demonstration carried out in an international conference.

II. OPAMPS IN ELECTRONIC ENGINEERING

OpAmps are widely used in electronics since they allow designers to implement several circuits without complex projects. In this section readers may get a brief history about OpAmps, their main characteristics and some available kits to support their teaching and learning.

A. Background history and main characteristics

According to the literature [13], the operational amplifier were firstly created by an American engineer named Loebe Julie in 1943. 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 AmpOps, 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 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 high input impedance, as well as the low output impedance, that mathematically allow the

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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 €.

establishment of particular relations between the input and output voltages. The generic circuit that represents an OpAmp constructed based on bipolar technology and some important mathematical relations is illustrated in fig. 1 It comprises an inverter and non-inverter inputs (v1 and v2), interconnected by a very high input impedance (Zin), and the output voltage (Vout), which is a result of a serial circuit with an output impedance (Zout) and a dependent voltage source (Vo). The traditional high value of Zin indicates that an OpAmp consumes very low current (bios current). It can also be seen that Vout depends on the Open Loop gain (Ao) and on the 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 that appear simultaneously and in-phase in both OpAmp inputs. The low value of Zout indicates that ideally a load circuit do not influence the AmpOp circuit operation, despite the current limit of the output (in the uA741 is about 20 mA). Parameters such as band-width, unbalance offsets, temperature influence, among others, should also be analyzed in every project, before choosing a particular OpAmp.

$$CMRR = \frac{A_0}{A_{cm}}$$

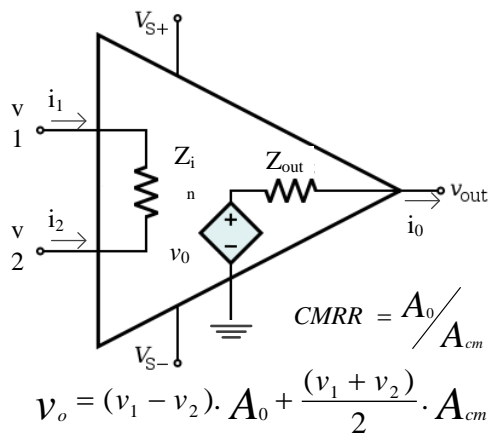$$v_o = (v_1 - v_2).A_0 + \frac{(v_1 + v_2)}{2}.A_{cm}$$

Fig. 1. General schematic of uA741 OpAmp and some mathematical relations.

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 classrooms, 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' learning autonomy. For this propose, the XL741 Discrete Op-Amp kit[7] developed by the Evil Mad Scientist Laboratories provides a transistor-scale replica of the µA741 integrated circuit. Despite very interesting for understanding its core circuits, a more practical approach for adopting AmpOps in electronic circuits is required, which justifies the several available kits in the market. These 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 AmpOps. Table 1 provides a list of some kits. 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 AmpOps, exposing students to a direct contact with electronic components.

TABLE 1. SOME EDUCATIONAL KITS WITH OPAMPS.

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
	TI Precision Amplifier Quickstart Kit
	http://www.ti.com/tool/AMPQUICKKIT-EVM

Only a few platforms are exclusively dedicated to teach and learn OpAmps and most of them don't integrate any simulation tool (e.g. [5][6]) that would allow students to complement experimental and practical activities required in any engineering course. Others, such as the NI-Elvis, are not specific dedicated to OpAmp circuits. The NI-Elvis platform allows users to setup any type of electronic circuits using a traditional breadboard, and permits the measurement of specific signals using a set of self-integrated instruments. In fact it is a good solution to provide in a traditional laboratory, but it is very expensive (about 2500 €), and it is not dedicated to teach OpAmps, which would require from students the same effort to implement electronic circuits as using a traditional breadboard and common laboratory instruments. Another

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[7] https://shop.evilmadscientist.com/productsmenu/762

interesting commercial product in the market is the Lab Volt FACET boards[8], 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 for easily changing its design and, in some situations, the components used to setup electronic circuits, which may limit the versatility required by a classical classroom.

Therefore, providing good and 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 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 AmpOps' 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 the 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,

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8 https://www.labvolt.com/products/facet-circuit-boards-and-courses.

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. The advantage of this approach is that all connections are automatically made, avoiding errors and facilitating the measurement of some specific signals.
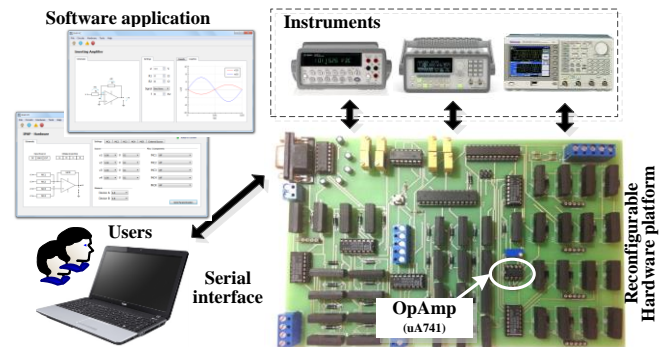

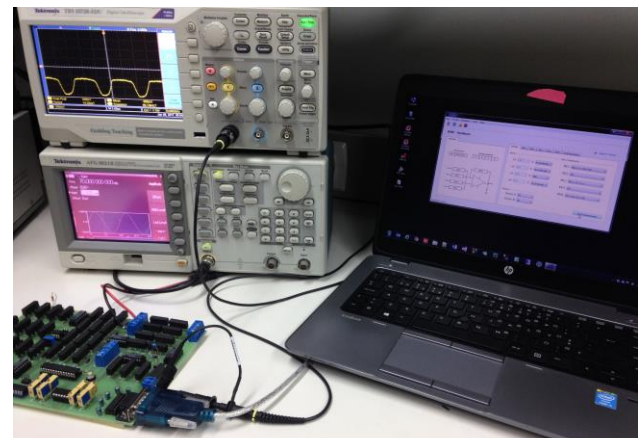Fig. 2. The overall architecture of implemented Kit.

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

B. Hardware platform

The main element of the kit is the reconfigurable hardware platform and, as already referred, the main element of the platform 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 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.
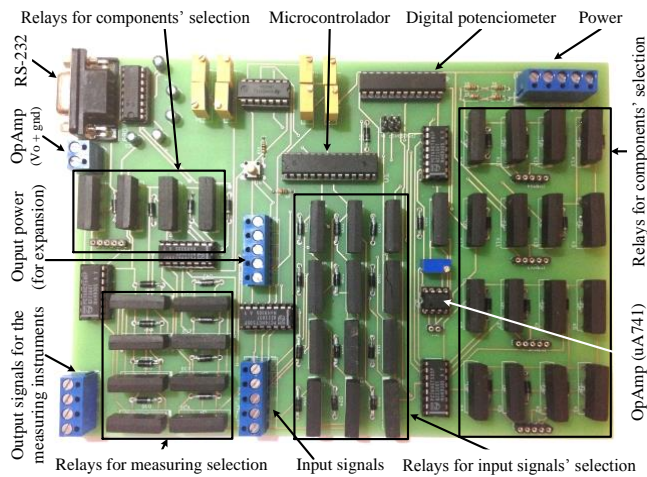

Fig. 4. Photography of the reconfigurable hardware platform with the main interfaces and the internal components.
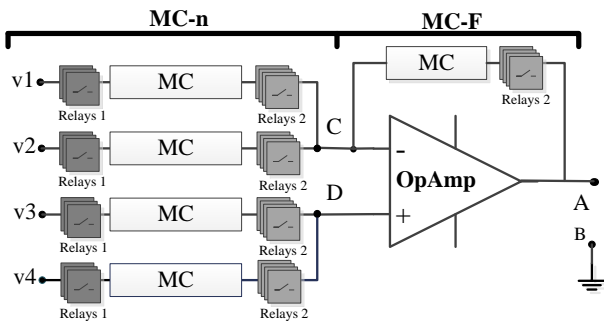

Fig. 5. Schematic with the architecture of the reconfigurable main circuit.

Once a MC is physically 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 (the teacher) to decide what kind of MC it would be

provided in the reconfigurable main circuit. In the exemplified case illustrated in fig. 7, the MC has 2 resistors, a short-circuit and a capacitor. By changing the position of a relay in the group relays 2, a particular component can be selected and inserted in the main circuit (fig. 5). The group relays 1 is used to select the type of signal used as an input of a particular reconfigured circuit, i.e. the signal source for each inverter or non-inverter terminal. Note that group relays 1 is only provided for the MC-n braches, while group relays 2 is provided for both type of branches, MC-n and MC-F.
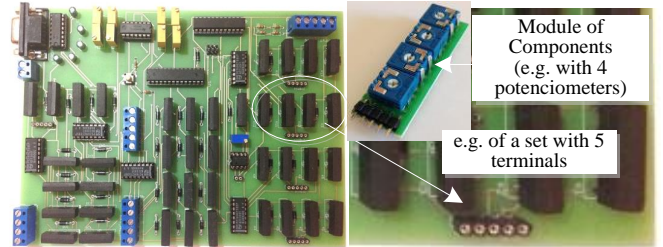

Fig. 6. Module of Components (MC) used to setup circuits based on the uA741 OpAmp.

To measure particular signals of a reconfigured circuit, users can place the probes of the selected instruments in particular points. As illustrated in fig. 8, and in accordance with points A, B, C and D, specified in the schematic presented in fig. 5, currently users can attach the instruments to the platform using 3 pairs of terminals; two of them able to be moved according to the position of two sets of 4 relays, and other with fix connections between the OpAmp output terminal (vo) and the ground (points A and B). Despite the limitations of the connecting points able to use by the instruments, users have some versatility to measure different voltages using, per example, a two channel oscilloscope and a multimeter.
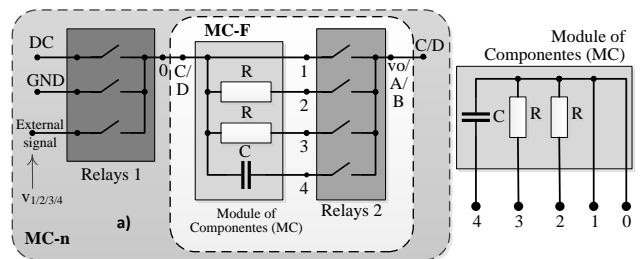

Fig. 7. Schematic for the selection of components using a MC with 2 resistors, 1 capacitor and 1 short-circuit;
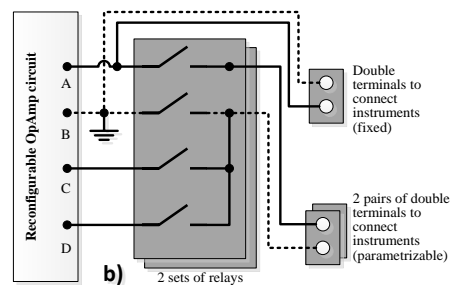

Fig. 8. Adopted schematic for selecting the measurement points on the circuit under test.

The selection of a particular component or a circuit provided by a MC, and the selection of each measurement point, is selected using 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. 9, 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[9]. The obtained results of those simulations can be archived in a data base 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.
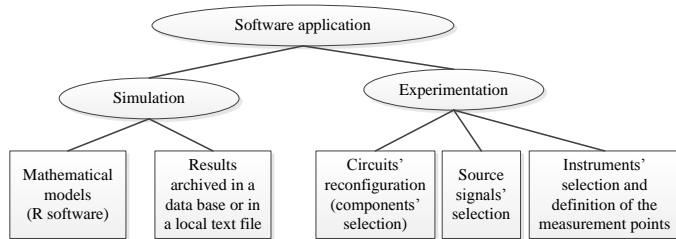

Fig. 9. Functionalities provided by the software application.

During the experimentation the software application basically 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.

As indicated, for simulating a particular circuit the software application should has the associated mathematical models defined in R scripts. These scripts do not need any recompilation, since they are interpreted by the R software

9 R is a free software for statistical computing and graphics (https://www.r-project.org/).

module that is installed in the PC together with the application. The parameters of the circuit able to simulate and the associated results retrieved from a particular simulation are all specified in a XML format file, facilitating this way their presentation in the interface of the software application. For experimenting a particular circuit, teachers must physically attach the required MC. The students may setup a particular circuit and describe the available component 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. 10, 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 files R files and enables the selection of other files to save the results obtained from the simulations (data base or a 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 that can be attached to the PC to facilitate users' observation of a particular measurement provided by an instrument;

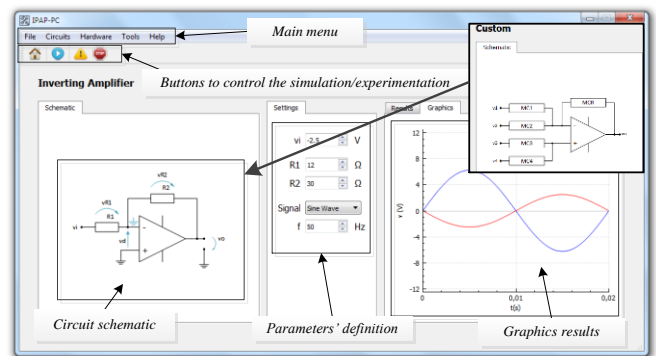- Help: Information about the software application.

Fig. 10. Example of an interface for simulating circuits.

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

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 data base 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. 11. 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.
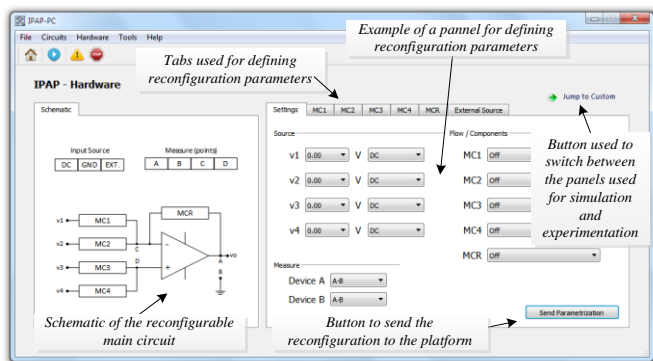

Fig. 11. Interface for reconfiguring and experimenting circuits.

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. Of course this approach may limit a relevant learning outcome that is the importance to expose 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 AmpOp-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]. As illustrated in fig. 12, a single PC can act as a server to access the platform and to enable a remote access to interfaces, similar to those provided by the software application. Once remotely accessible, a single device connect to the Internet (e.g. a PC or a smart phone) would be able to remotely simulate, reconfigure and experiment the circuits. In this situation some other considerations would be posed, namely the best solution to access the kit. The software application can run on the users' PC or remotely accessible. In the first situation all the simulations are made in the users' PC, while in the second situation the application should be installed in the server and, when a student wants to simulate a particular circuit it can trigger a thread to handle each particular request or simple respond to each request according to sequential accesses, as in a waiting list, such as a FIFO (First-In First-Out).

The access to the hardware platform can be more demanding, and two possible accessing modes can be considered, 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 connect to the platform whenever they want, defining the configurations and acquiring results. There is no time reservation to access the platform since the commands send and the retrieved responses can be also acquired based on a FIFO waiting list. Both solutions can be considered, although, and in particular for current kit, the asynchronous mode brings more advantages towards the synchronous mode. Despite more complex to implement, the asynchronous mode is more adequate when the remote experiments do not comprise moving elements, as in the current solution. By using the asynchronous mode students may select the configuration they want to experiment and wait for the results. This type of approach simplify the accessing management and provides more accessibility to the platform, since it is not reserved for a period of time, being all this process transparent for students. 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. Although, 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, the ERASMUS+ project,

named VISIR +[10], recently finished in October 2018, and an ongoing project named PILAR[11], are wide spreading their adoption in Latin American and European countries by integrating it as an important leaning object of a common electronic engineering course [13]. 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 education 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.
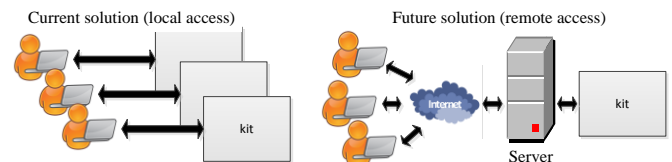

Fig. 12. Current and future solution for accessing to the kit.

Therefore, current kit can be applied in an engineering course given support to the experimental lessons since ir provides a simulation tool plus a reconfigurable and expandable kit that allow the conduction of real experiments with AmpOps without the necessity of setting up circuits from scratch. However, it requires some improvements before its adoption. The remote access is probably the most relevant one and 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 USING THE KIT IN EDUCATION

To understand the possible relevance the kit may have to improve the way AmpOps can be teach (and learn) in electronic engineering, the kit was demonstrated in a technical session of the international conference named exp.at'17[12] held at the University of Algarve. Based on a submitted abstract, already published in [21], the kit was demonstrated to some participants, most of them teachers of electronics, and some opinions were acquired.

The indicated conference was selected since it offers to the participants an opportunity to present their recent work and in

10 VISIR + - Educational Modules for Electric and Electronics Circuit Theory and Practice Following an Enquiry-based Learning and Teaching Methodology Supported by VISIR [oct. 2015 – oct. 2017].
11 PILAR - Platform Integration of Laboratories based on the Architecture of VISIR. [oct. 2017 – oct. 2020].
12 Exp.at'17 is a joint organization of the University of Porto and the University of Coimbra, held at University of Algarve, Portugal, with its collaboration and the technical support of IEEE (IEEE Industrial Electronics Society and IEEE Education Society) and the Portuguese Engineers Association. (http://expat.org.pt/expat17/)

particular it includes exhibition sessions to present demo products to the research community. It was precisely in one of those exhibition sessions that the kit was demonstrated to some participants, and their opinion and their perception for using the kit in education was acquired though a small quiz filled by 10 of them. 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, and to pose questions about it. After this process, they were invited to fill-in the quiz. This quiz, whose responses are presented in table 2, was mainly divided in 3 parts: Part I to understand the participants' background; part II to evaluate their interest in the kit, and part III to verify if they are receptive to adopt this kit in their classes.

Despite the short number of participants (10 participants), the obtained results should be considered relevant to evaluate the proposed solution (kit), since these participants are active researchers in the area, and some of them have many years of expertise teaching electronics. Generically observing the results presented in the table, it is evident that the kit triggered the interest to the participants, since the large majority indicated that they would like to use it in their classes, even if they are not currently teaching the thematic. The remote access was considered 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).

TABLE 2: 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"

It is also interesting to note that participants selected many relevant benefits using the kit in education, in particular the promotion of experimental competences to the users (students), and most of them see its use as a contribution to contextualize the theoretical part of classes. In which concerns the possible difficulties for using the kit, there were not 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. From our analysis this indicates that from the teachers' point of view the kit will 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 responses it is reasonable to say that teachers see a technical support to use the kit as fundamental, in order to overcome possible problems that may occur. 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, and after some punctual conversation during the presentation, justifies and incentivize some improvements to the kit, in particular the development of a remote access, which is also our intention to do in the near future. After the implementation of this feature, it is also our intention to evaluate the kit in a real educational scenario, allowing students to validate it to understand and eventually confirm some of the perceptions indicated by participants and by the authors of this paper.

VI. Conclusions

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, namely 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.

Therefore, 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 validated 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 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 the components and the implementation in the PCB board). 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.

ACKNOWLEDGMENTS

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