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Teaching of electronic circuits for measuring technology at the Faculty of electrical engineering, department of measutrement, CTU in Prague

A R T I C L E I N F O

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A B S T R A C T

The paper outlines teaching methods for analog and analog-to-digital electronic circuits used to process and digitize signals from common physical sensors at the Department of Measurement, Faculty of Electrical Engineering, Czech Technical University in Prague. The methods include using single-purpose functional units, a virtual instrumentation suite, and analog systems for teaching. The use of simulation programs supports the teaching of these circuits. It has proven to be very effective in laboratory classes. Class success rates and student survey ratings support the effectiveness of this teaching approach.

1. Introduction

The teaching of analog and analog to digital electronic circuits at the Department of Measurement, Faculty of Electrical Engineering, Czech Technical University in Prague (CTU in Prague) has a long history. During these times, a balance between a practical approach based either on discrete electronic components assembly or deploying functional units of analog processing circuits and a purely theoretical approach deploying circuit modeling software has been deployed. This was verified at the department during the COVID-19 pandemic [1–3].

From the beginning of the 1990s, a set of functional units was used for training, consisting of differential, instrumental, integral, isolation, and sampling amplifiers, multiplexers, logarithmic and exponential amplifiers, operational rectifiers, RMS converters, peak detectors, A/D and D/A converters [4].

Since the end of the 1990s, teaching using these units has been supplemented by simulation of their properties using the NI Multisim simulation program from National Instruments. This step expanded the number of circuits whose properties were also simulated and verified with fewer demands on the number of contact hours. Along with this innovation, the Department of Measurement developed the LABORO educational kit, including power supplies, a functional generator, two disposable TTL pulses, eight indicator LEDs, and four seven-segment displays. This kit was designed to verify the properties of typical A/D and D/A circuits that students connected to a contact field. In the following years, educational kits from National Instruments replaced this kit, enabling broader teaching methods.

At present, the teaching of electronic circuits for measurement technology at the Department of Measurement of the CTU in Prague is designed in such a way that students first simulate the properties of these circuits and then connect some of these circuits on the educational platform systems. The courses aim to compare the properties of the circuits obtained by their simulation with the properties of identical circuits connected to the kit.

The laboratory of analog electronic circuits includes three subjects: Analog Signal Processing and Digitalization, Construction of Medical Systems, and Circuit Technology. The first subject is dedicated to methods for pre-processing, digitalization, and reconstruction of continuous signals. It is focused on strategies for achieving high precision in transmission and suppression of spurious components. The laboratory classes are divided into two parts: the first includes classical tasks, and the second focuses on individual projects of a typical data acquisition system design. The Construction of Medical Systems class deals with the general principles and principles of design and construction of medical devices and systems. It includes technical standards and their requirements for the design, construction, and operation of medical electrical equipment. Design and construction of basic blocks of medical devices and their electromagnetic compatibility. The last class – Circuit Technology, introduces students to the basic types of circuits and building blocks of digital devices for measuring and generating electrical signals. Emphasis is placed on the interconnections of individual circuits regarding accuracy in analog or analog-digital circuits.

As written above, the courses also include individual projects in which students design the solution of the circuit according to the assignment, simulate its properties, and connect the circuit to the breadboard or educational platform. The next stage of teaching can be the design of the printed circuit, it's fitting with components, and the commissioning and determination of the parameters of the circuit implemented in this way.

2. Methods

The role of laboratory classes in electrical engineering is essential [5]. The evolution of teaching electronic circuits at the Department of Measurement included from the simple breadboards and LABORO educational kit to the professional platforms. After several years of its use, the teaching conceived in the way of a combination of practical connections and simulations has proven to be very effective since the design and simulation of circuits, or their connection to the breadboard, can be prepared by students at home, and the contact time can then be

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used for consultations and reviving circuits in the laboratory classes [6] or [7].

2.1. Analogue and analogue-digital circuits functional units

The teaching set of these units was developed in 1993 at the Department of Measurement, CTU FEL in Prague. It contains differential (Fig. 1), instrument, integration, isolation, logarithmic, exponential and sampling amplifiers.

This teaching set includes active 2nd order low-pass and high-pass filters, band-pass and band-stop filters with adjustable step response, switched filters, rectifiers with operational amplifiers (OA), logarithmic RMS converters, peak detectors, controlled rectifiers, phase shifters, U/f and f/U converters, and 8-bit A/D and D/A converters (Fig. 2). The power supply for these circuits is provided by an external 5 V and ±12 V power supply.

The set of functional units is designed for the classical teaching method. In this method, students set the parameters of the input signals and use separate measuring instruments (such as power supplies, digital voltmeters, oscilloscopes, and logic analyzers) to determine the parameters of circuit output signals. Some of these units are used to teach subjects in the bachelor's program of study.

In addition to these single-purpose functional units, exchangeable functional boards of analog and analog-digital circuits are used for practical teaching of the basics of electronics and circuit technology in the bachelor's stage. Fig. 3 shows a quad OA board with a set of resistors, capacitors and diodes, making it possible to measure the properties of OA and verify the properties of linear and non-linear analog circuits including differential, instrumentation and integration amplifiers, passive and active filters, logarithmic and exponential amplifiers and active and passive AC signal rectifiers.

In the master's stage of teaching, which is based on the knowledge of students in the bachelor's stage of study, development kits are used for the advanced level of teaching, on which students verify the properties of more complex circuits, which they can also connect to the kit's non-soldering contact field.

Fig. 4 shows an eight-bit A/D converter board with an 8-bit D/A converter with an adjustable voltage source. This board makes it possible to verify the properties of ADC and DAC, including a reconstructed sine signal with an adjustable number of samples in one period, for which its frequency spectrum and Total Harmonic Distortion are determined.

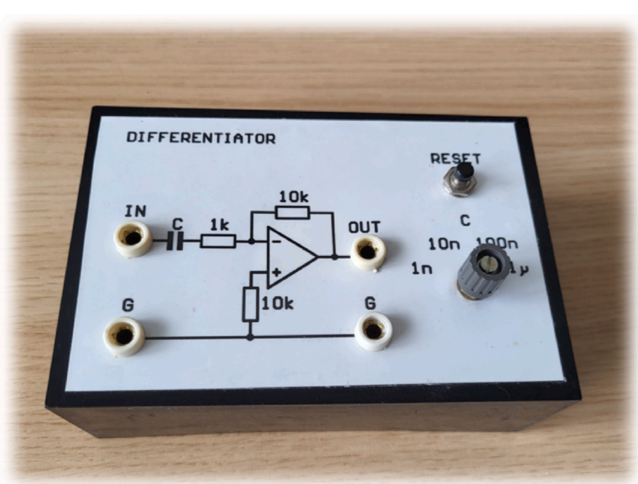


Fig. 1. Differentiator unit developed at Department of measurement.

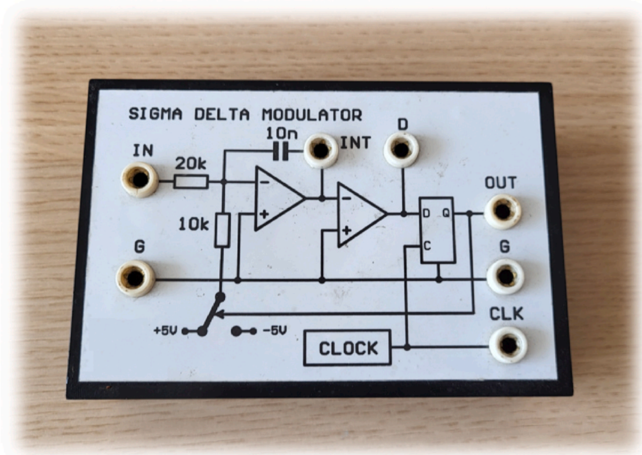


Fig. 2. Sigma Delta modulator functional unit developed at Department of measurement.

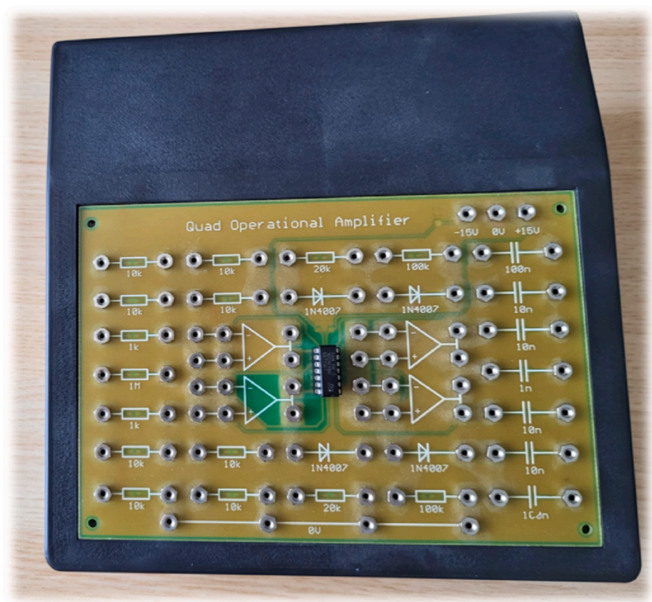


Fig. 3. Exchangeable functional board with operational amplifier.

2.2. Engineering laboratory virtual instrumentation suite

The commercially available educational system NI ELVIS offers a hands-on approach to teaching practical and experimental engineering skills. The first model of the system was the NI ELVIS I, which consisted of a panel containing, in addition to the power supplies, a ±5 V variable voltage source, a function generator with a frequency range of 1 Hz–100 kHz with a variable amplitude in the range of ±10 mV to ±5 V and a DC voltage offset in the range of ±5 V.

The first educational model allowed the teaching of electronic circuits employing interchangeable panels on which the characteristics of passive R, L, and C circuits, voltage amplifiers, instrumentation amplifiers, passive and active first and second order filters, logarithmic and exponential converters, multipliers, power supplies and TTL of basic and medium integration digital circuits whose digital signals were generated by pushbuttons and indicated by LEDs.

The following NI ELVIS II model differs from the previous model by incorporating a continuous signal function generator, a two-channel digital oscilloscope, a digital multimeter, a digital signal generator,

Fig. 4. Exchangeable functional board with ADC and DAC circuits.

and a logic analyzer. This learning system includes interchangeable breadboards on which students can connect specified electronic circuits by themselves and verify their properties with built-in measuring instruments.

The control of the instruments, the data transfer to a PC, and the processing and presentation of the measurement results are handled by a USB interface and the graphical programming package LabVIEW Signal Express. The newest system version is NI ELVIS III, which is also equipped with a wireless connection to a PC.

2.3. Analog system lab kit

Another commercially available educational kit, the MikroElektronika ASLKPRO University Kit, offers a combination of OA and three wide-bandwidth precision analog multipliers verification of the properties of inverting and non-inverting voltage amplifiers, integration and derivative amplifiers, analog filters, multipliers, phase detector, voltage controlled oscillator, PLL circuit, DC-DC converter, low-loss regulator, amplifier with digitally controlled amplification and digitally controlled function generator. In addition to these circuits, other circuits, such as differential and instrumentation amplifiers, can be verified using this kit. It proved to be a good tool for general-purpose electronic circuit design and verification for undergraduate engineering students, allowing them to perform various laboratory cost-efficient experiments.

2.4. Simulation program

The teaching of electronic circuit properties for instrumentation is enhanced by using the NI MULTISIM Education simulation program. This program allows simulation of circuit properties in both time and frequency domains, including DC Operation Point, AC Analysis, Single Frequency Analysis, Transient Analysis, Fourier Analysis, Noise Analysis, Noise Figures Analysis, Distortion Analysis, DC Sweep Analysis, Sensitivity Analysis, Parameter Analysis, Temperature Analysis, Worst Case Analysis, and Monte Carlo Analysis. Additionally, the program enables users to save and export data to MS Excel for further processing and to convert circuit diagrams to the breadboards of the NI ELVIS II teaching systems. The extended version of the MULTISIM 14 simulation program also supports PCB design, component location display on the PCB, and creation of manufacturing documents.

An example of the laboratory tasks that can be implemented in MULTISIM is shown in Figs. 5 and 6. Fig. 5 illustrates a simulated Δ-Σ modulator circuit with measured waveforms at important points of the circuit, including the input signal, integrator, comparator output, and the output.

Fig. 6 shows a simulated circuit of an 8-bit A/D-D/A system for digitization and reconstruction of sinusoidal signals, including their waveforms.

The part of the introduced classes is also an independent project in which students design an electronic measuring circuit according to the assignment, simulate their properties, and verify them on a breadboard. The next phase of the course can be the design of printed circuit boards of these circuits, their mounting with components, powering up, and determination of implemented circuit parameters.

3. Discussion

The presented teaching method has several advantages. Firstly, it allows students to understand and verify electronic circuit properties using a simulation program, which can simulate both static and dynamic properties in the time and frequency domains. Students can also conduct sensitivity analyses to observe how changes in components, such as variations in temperature or parts tolerances, affect the circuit. Advanced techniques like the Monte Carlo and Worst Case methods can be used for these analyses.

Additionally, this approach helps students comprehensively understand designing and constructing electronic measuring devices and systems. This knowledge is not just theoretical; students can immediately apply what they have learned to their projects. Furthermore, the skills and insights gained through this method are directly transferable to their future technical practice, ensuring that they are well-prepared for professional challenges in the field of electronics [8,9].

Over several years, this educational approach has proven to be highly effective. By allowing students to design and simulate circuits at home, they can make more productive use of their contact time with lectors. During these sessions, they can consult with instructors and power up the circuits in the laboratory, enhancing their practical learning experience.

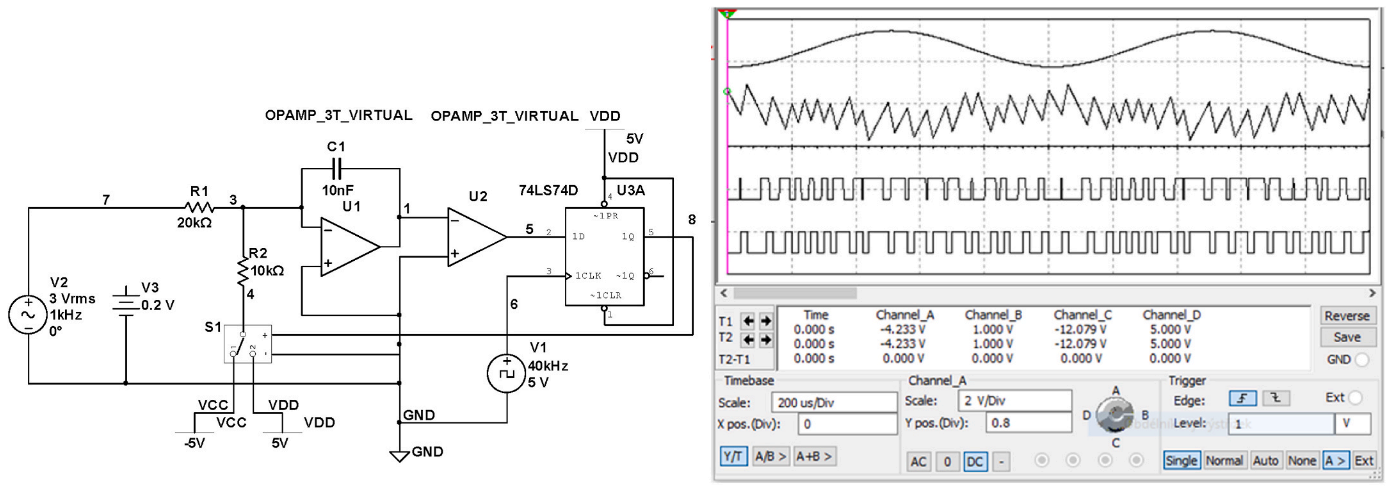
Statistical data on success rates support this effectiveness and student survey results from the past eight years, as illustrated in Fig. 7.

Surveys conducted with at least 40 master's degree students per year reveal a significant increase in the success rate, which has risen from 75 % to 100 % in the most recent year. The class ratings have also shown an upward trend, approaching a perfect 100 % rating.

These findings suggest that integrating multiple hands-on educational methods with simulation software markedly improves the teaching effectiveness of today's students. This combination enhances students' understanding and practical skills, positively influences their academic performance and satisfaction with the courses, and can be an excellent addition to interactive learning [10,11].

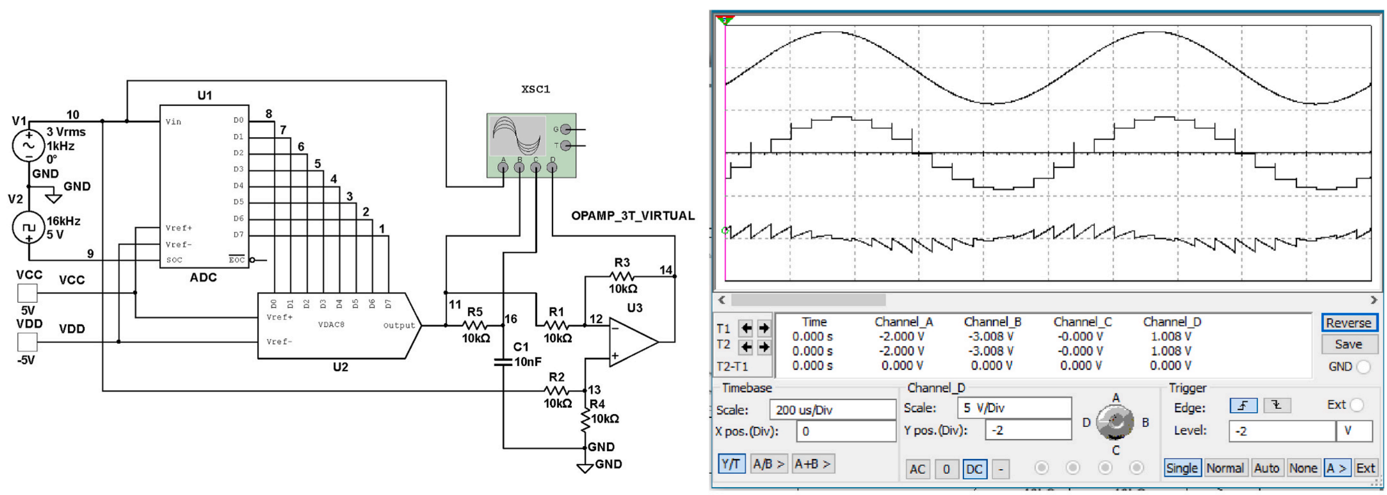
4. Conclusions

The article introduces teaching methods for analog and analog-to-digital electronic circuits classes at FEE, CTU in Prague. It demonstrates how support tools have evolved over the years. The right balance between hands-on and simulation-only tasks has been achieved by using a combination of commercially available educational systems and simulation software. Teaching electronic circuits using evaluation boards and kits is significantly more engaging and effective than solely modeling circuits in a computer simulator. This approach enables students to work with real circuits and actual electrical quantities, enhancing their hands-on experience. Compared to implementing a complete circuit on a printed circuit board or using a breadboard, this method is also more time-efficient. It allows students to study numerous



a) simulated circuit b) signal waveforms

Fig. 5. Delta sigma modulator.



a) simulated circuit b) signal waveforms

Fig. 6. 8-bit A/D-D/A system for digitization and reconstruction of signals.

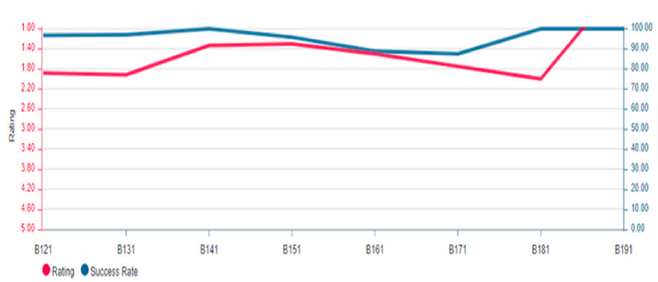


Fig. 7. Class statistic results through eight years.

circuits within the limited time available during laboratory exercises, thereby maximizing their learning opportunities. The statistics from the last eight years also confirm the effectiveness of this approach.

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References

[1] J. Svatos, J. Holub, J. Fischer, J. Sobotka, Online teaching of practical classes under the Covid-19 restrictions, Measurement: Sensors 22 (2022) 100378, https://doi.org/10.1016/j.measen.2022.100378.

[2] J. Svatos, J. Holub, How the COVID-19 changed the hands-on laboratory classes of electrical measurement, Acta IMEKO 11 (4) (2022) 1–7, https://doi.org/10.21014/actaimeko.v11i4.1301.

[3] J. Svatos, J. Holub, J. Fischer, J. Sobotka, Online teaching at CTU in Prague aka university under COVID restrictions, Measurement: Sensors 18 (2021), https://doi.org/10.1016/j.measen.2021.100121.

[4] J. Vedral, J. Svatos, Analog Signal Processing and Digitization in Measurement, Czech Technical University, Prague, 2020. ISBN 978-80-01-06717-8.

[5] L.D. Feisel, A.J. Rosa, The role of the laboratory in undergraduate engineering education, J. Eng. Educ. 94 (1) (2005) 121–130.

[6] B. Balamuralithara, P. Woods, Virtual laboratories in engineering education: the simulation lab and remote lab, Comput. Appl. Eng. Educ. 17 (2009) 108–118.

[7] M. Jing, J. Nickerson, Hands-on, simulated, and remote laboratories: a comparative literature review, ACM Comput. Surv. 38 (3) (2006).

[8] Z. Psenakova, D. Gombarska, M. Smetana, Implementation of laboratory exercises in the process of teaching the subject of electrical circuits, in: 2024 ELEKTRO (ELEKTRO), Zakopane, Poland, 2024, pp. 1–5, https://doi.org/10.1109/ELEKTRO60337.2024.10557096.

[9] H. Fan, et al., Reform, innovation and practice of electronic circuit teaching, in: 2023 32nd Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE), Eindhoven, Netherlands, 2023, pp. 1–5.
[10] M.H. Fino, Challenges in teaching electrical circuit Analysis to millennials, in: 2018 3rd International Conference of the Portuguese Society for Engineering Education (CISPEE), Aveiro, Portugal, 2018, pp. 1–4, https://doi.org/10.1109/CISPEE.2018.8593460.
[11] R. Lehto, Interactive lecturing techniques, in: 2011 IEEE International Symposium of Circuits and Systems (ISCAS), Rio de Janeiro, Brazil, 2011, pp. 605–608, https://doi.org/10.1109/ISCAS.2011.5937638.

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