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LEARNING THE BASICS OF ANALOGUE-TO-DIGITAL CONVERSION - AN EXPERIMENTAL APPROACH

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Abstract – This paper describes a set of computer-based experiments, based in LabVIEW, designed to help engineering students learn the basic concepts of analogue-to-digital conversion, such as quantization and sampling. The course was taken by Electrical and Computer Engineering students at the Electrical and Computer Engineering Department of the Faculty of Engineering of the University of Porto. A broader aim of this pedagogical experiment was to increase the students' motivation and to increase their learning effectiveness.

Keywords: Electronic instrumentation, analogue-to-digital conversion, computer-based learning

1. INTRODUCTION

A number of authors have proposed the use of suitable software tools to enhance learning electricity and electronics [1]-[3]. In [1], the authors present the organization of laboratories for teaching basic electricity and electronics for undergraduate students including a set of hardware-software based experiments that are used in four courses. A. Luchetta et al. [2] describe a program that was developed for automatic symbolic and numerical analysis of linear circuits. A virtual laboratory, developed in a windows framework, was presented in [3]. The proposed virtual instrumentation workbench allows the visualization of time and frequency effects of analog-to-digital conversion and in digital signal processing. Reported teaching impact has been mixed, with one author noting that failure rates were not changed with the introduction of the new learning aids [1], and another giving a cautiously positive evaluation of the usefulness of the computer based teaching tools [4]. However there seems to be no disputing the importance of laboratory work in engineering courses [5] and the growing use of computer tools not only as learning aids but also as objects of the learning process.

We present in this paper a set of computer-based experiments that enable students to explore the concept of analog-to-digital conversion. This set of experiments is part of a larger set of computer-based experiments developed for an Electronic Instrumentation course for the Electrical and Computer engineering students at the Faculty of Engineering of the University of Porto. The objectives of these experiments were: first, to illustrate and reinforce the concepts introduced in the lectures and tutorial sessions thereby increasing the students' learning effectiveness; second, to motivate the student's interest in the course subject, in general. As an added benefit this allows the students to get a first exposure to the basics of programming in the LabVIEW environment [6, 7].

To achieve these objectives, the computer-based experiments developed for this course focused on the main theoretical concepts, such as measurements uncertainty, rms measurement techniques, analog-to-digital conversion and signal acquisition. The experiments are interactive, letting the students change parameters, and immediately see the results, often while the programs are running. The aim was to help the students to understand the reasons why a particular choice of parameters gives a particular result, leading them to explore the subjects presented in the lectures. Since the students work in groups of two, all on the same experiment simultaneously, this leads to frequent information exchange among students and with the instructor, which is facilitated by the informal lab environment. The students are also asked to analyse the program code, and later build their own program.

The laboratory applications presented here can be tuned according to the degree where the course is inserted. This means that students of Informatics Engineering may be oriented towards the design of virtual instruments. While for example, students of Mechanical Engineering could focus on the acquisition and processing of mechanical quantities measured by specific transducers.

2. THE PROGRAMMING ENVIRONMENT

The programming environment in which experiments were developed is LabVIEW. It is an environment to which the students adpapt with relative ease, being based on a graphical programming language. The resulting programs are called "virtual instruments" or VIs. These virtual instruments are composed of a front panel and a graphical representation of the program code, in the form of a data flow diagram, called the diagram. The front panel supplies a graphical user interface to the program, using elements common in instrumentation front panels, such us dials, push buttons, digital readouts and graphical screens. The diagram is the graphical representation of the code and it is, in fact, the way in which the code is constructed, i.e. graphically, by manipulating a set of graphical symbols representing input and output variables, subroutines and their interconnections.

In this course, the basic concepts of LabVIEW are introduced in a two-hour classroom session using a PC with video projection. The students then learn LabVIEW in the laboratory, by first examining how the experiments are put together, playing with them, and finally creating a program of their own, using some parts of the experiments as building blocks. The experience showed that students assimilated quite easily the basics of LabVIEW programming in this way.

3. LABORATORY EXPERIMENTS

A total of four computer-based laboratory experiments were designed using LabVIEW, illustrating basic principles of measurements uncertainty, rms measurement techniques, analog-to-digital conversion, and signal acquisition. Each of the experiments consisted of one or more LabVIEW programs. All the students in each laboratory session, working in groups of two, execute the experiments simultaneously. In our experience, a set of common laboratory experiments is a good way to foster the interaction among the students, stimulating teamwork and collaborative learning. The experiments are structured in such a manner that gradually leads the students to explore the LabVIEW environment. The students begin by simply using the VIs as given and at later stages are asked to change the VIs to obtain different functionalities.

These experiments had a twofold objective: technical and pedagogical. The students are introduced to the measurement methods using virtual instruments, by guided experimentation using mathematically defined functions. After executing the experiments on analog-digital conversion which are the subject of this paper, they tackle a set of experiments on data acquisition of real signals, using a data acquisition board installed in the PC. In these, students are faced with technical aspects relating for instance with input noise and offset, and sampling rate limitations imposed by the hardware.

In the next section we present the set of experiments which formed the third of the laboratory experiments in this course, namely on analog-to-digital conversion.

4. ANALOG-TO-DIGITAL CONVERSION

This section presents the set of programs that were developed to help students work on some of the basic concepts of time discretization (sampling) and amplitude discretization (quantization). These lead to questions about the adequate sampling rate and aliasing problems, and also about the effect of the number of bits used, the relation between the analog range, the number of bits and the quantization interval and quantization noise.

The relation between the input of the uniform quantizer, $v(t)$, and the corresponding output, $x_q(t)$, is implemented by the expression, valid in the range $[V^-, V^+ - Q/2]$, in which the function *Round* returns the nearest integer:

$$x_q(t) = Round\left(\frac{v(t)}{Q}\right) \qquad (1)$$

In this expression Q is the quantum, or the value of the quantization step. For a quantizer with n bits, having as maximum and minimum values V^+ and V^-, the quantum Q is given by

$$Q = \frac{V^+ - V^-}{2^n} \qquad (2)$$

For the usual case of $V^+ = -V^- = V$, the expression for $x_q(t)$ returns a value of 2^{n-1} for values of $v(t)$ in the interval $[V^+ - Q/2,\ V^+]$ which is not the desired result; in an uniform bipolar quantizer the largest positive digital value generated should be $2^{n-1}-1$, as shown in the example in figure 1(a) for a 4-bit quantizer with V=8 Volt. The program incorporates the appropriate correction, subtracting 1 whenever $x_q(t)$ is 2^{n-1}. Figure 2 shows the LabVIEW diagram that implements this function. As a consequence of this property the quantizer creates a peak quantization error of Q in the topmost quantization interval of its range, compared with $Q/2$, in the rest of the range, as shown in figure 1(b) [8, 9].

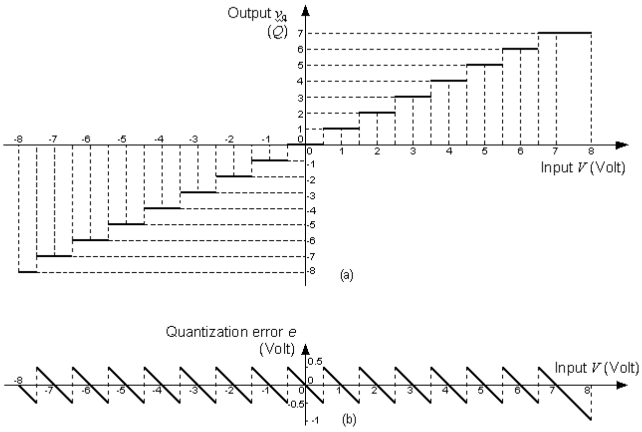


Figure 1. Quantizer characteristic (a) and quantization error graph (b) of a 4-bit quantizer with a ±8 Volt analog range.

Figure 3 illustrates the front panel of the experiment, where the student has the possibility to observe the quantization effects for several input signals (sine, triangular, rectangular and sawtooth waveforms) and different number of bits. Both the quantizer and the input signal have an input range of -2^7 to 2^7. The input signal amplitude can be controlled within this range.

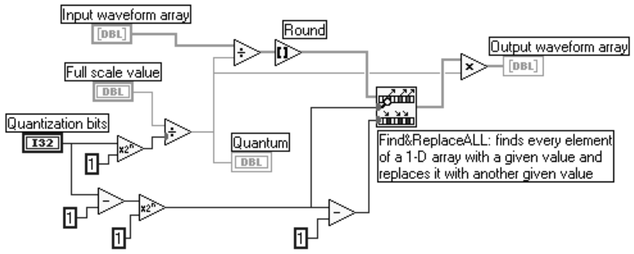
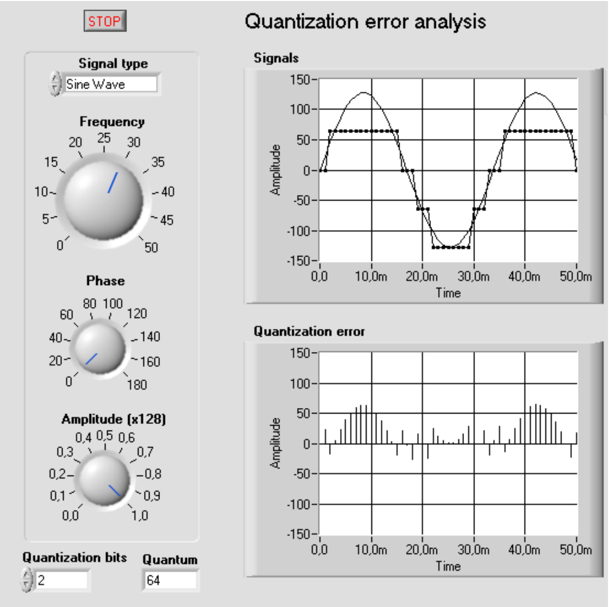


Figure 2. Quantizer diagram.



Signal type: Sine Wave

Quantization bits: 2

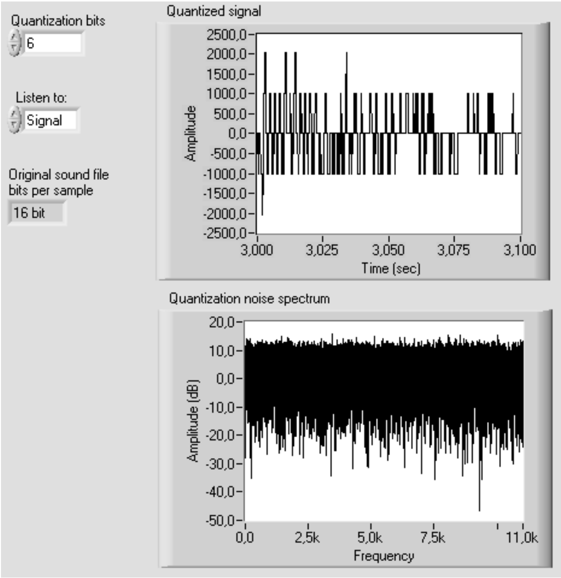
Quantum: 64

Figure 3. Analog-to-digital conversion showing the effect of quantization.

The quantization error $e(t)$ [$e(t) = x_q(t) - v(t)$] is also plotted in the front panel, allowing the students to observe the error in relation to the original and quantized waveforms.

The effect of the larger quantization error in the topmost quantization interval is clearly visible and prompts questions about the reason why the error is larger near the positive peaks of the input waveform. Experiments such as the obvious reduction in the amplitude of the input waveform can then be carried out to confirm the theoretical explanation.

The sense of the importance of the number of quantization bits can be further conveyed to the students with another program, which allows the students to listen to sounds, using one of several sound files in *.wav* format, with different numbers of quantization bits. The students can listen to the sound or to the quantization noise, after choosing the number of quantization bits. They can also look at the graphical representation of the waves, as shown in the front panel in figure 4 and at the quantization noise power spectrum. Through this they can observe that the noise is approximately white and that the level increases by about 6 dB for every quantization bit that is removed, supporting the usual theoretical analysis [9]. This can lead the students to investigating the question “is the quantization spectrum always white?”. The correct negative answer [10] can be obtained experimentally by modifying the experiment in figure 3, in order to obtain the quantization noise spectrum resulting from quantizing periodic waveforms, which the students can do easily, almost by cutting and pasting between the two diagrams.



Quantization bits: 6

Listen to: Signal

Original sound file bits per sample: 16 bit

Figure 4. Sound player panel showing a sound waveform fragment at 6 bits quantization.

Another program, whose panel is shown in figure 5, is used to illustrate the sampling process, including the aliasing phenomenon. When this program is running the students can modify the frequency of the sine wave that is fed into the sampler, and observe both the resulting sampled sine wave and its power spectrum. The sampling frequency is fixed at 1 kHz, a notional value since the waveform is synthesized in the program. The number of samples generated is fixed at one thousand, corresponding to one second of “time”. As the students increase the input frequency towards 500 Hz, they can see the spectral peak moving to the right, and they can see that the sampled waveform overlaps the input signal. When the input frequency goes above 500 Hz, the students observe the spectral peak moving down again towards zero frequency, and the sampled waveform becoming a lower frequency version of the original waveform. The frequency of the aliased waveform f_a can be checked with the theoretical value, $f_a = f_i - f_s/2$, where f_i is the input signal frequency and f_s is the sampling frequency. Students’ lab reports showed that this very graphic and interactive demonstration was successful in promoting understanding of the aliasing phenomenon.

In the panel shown in figure 5 the frequency values were restricted to integer numbers to avoid energy spreading effect over the spectrum due to an input signal with a non-integer number of cycles. The students can then easily change the experiment so that the frequency values are no longer integer, motivating the introduction of the subject of windowing; several different types of windows can be discussed, and tried out, as shown in figure 6.

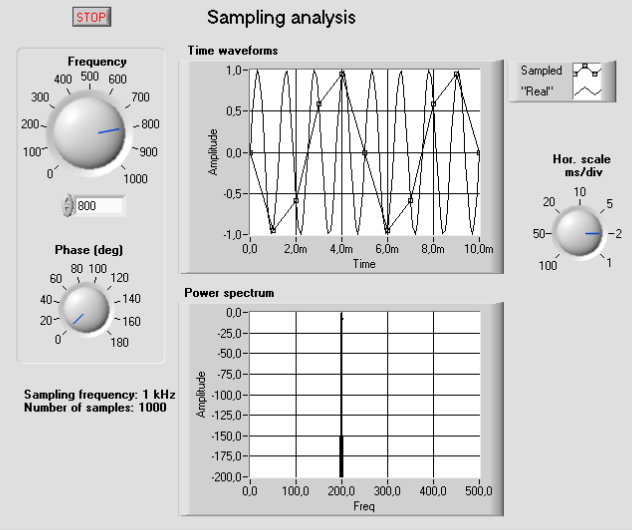


Figure 5. Analogue-to-digital conversion showing the effect of undersampling.

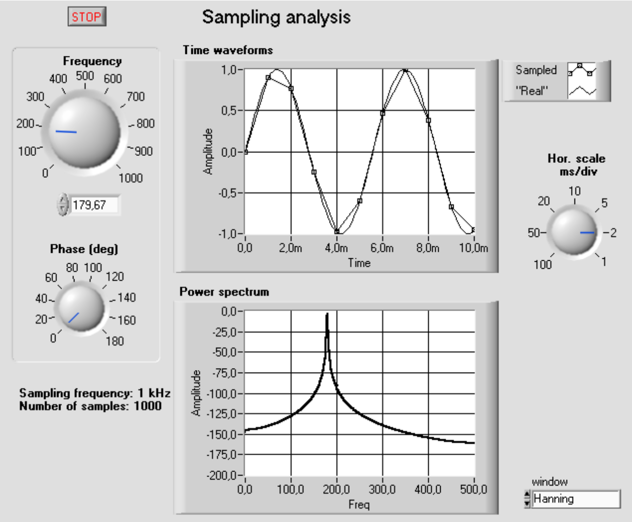


Figure 6. Analog-to-digital conversion: sampling with windowing.

5. DISCUSSION

The laboratory experiments based on LabVIEW programs that were presented here, along with the other experiments conceived for this course, provide a rich formative environment for students, either in electronics or non-electronics engineering courses. The experiments not only provided rigorous and insightful verification of theoretical concepts, but they also have the potential to motivate the students to explore theoretical concepts beyond the experiments.

Student interest in the course improved, measured by the attendance numbers at the lectures, since lecture attendance was not compulsory. It is noticeable that the students enjoy working with the computer based experiments and evaluation of their laboratory reports indicates a good grasp of the theoretical concepts.

Objective evaluation of the impact of the computer based experiments in the students' learning cycle will be conducted by the end of the course.

REFERENCES

[1] Denise Consonni, Antonio Carlos Seabra, "A Modern Approach to Teaching Basic Experimental Electricity and Electronics", *IEEE Transactions on Education*, vol. 44, no. 1, pp. 5-15, Feb. 2001.

[2] A. Luchetta, S. Manetti, "SAPWIN – A symbolic Simulator as a Support in Electrical Engineering Education", *IEEE Transactions on Education*, vol. 44, CD-ROM, May 2000.

[3] Jose M. Grima Palop, Jose M. Andres Teruel, "Virtual Work Bench for Electronic Instrumentation Teaching", *IEEE Transactions on Education*, vol. 43, no. 1, pp. 15-18, Feb. 2000.

[4] Claudio A. Cañizares, Zeno T. Faur, "Advantages and Disadvantages of Using Various Computer Tools in Electrical Engineering Courses", *IEEE Transactions on Education*, vol. 40, no. 3, August 1997.

[5] Norrie S. Edward, "The role of laboratory work in engineering education: student and staff perceptions", *International Journal of Electrical Engineering Education*, vol. 39, Issue 1, pp. 11-19, January 2002.

[6] Robert H. Bishop, "Learning with LabVIEW", Addison Wesley, 1999.

[7] National Instruments, "LabVIEW Measurements Manual", 2000.

[8] Analog-Devices, "Analog-Digital Conversion Handbook", Prentice-Hall, 1986.

[9] Sergio Franco, "Design with Operational Amplifiers and Analog Integrated Circuits", 2^{nd} ed., McGraw-Hill, 1998.

[10] Robert M. Gray, "Quantization Noise Spectra," *IEEE Transactions on Information Theory*, vol. 36, no. 6, pp. 1220-1244, November 1990.

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