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An ECG Lab Project for Teaching Signal Conditioning Systems in a Master's Degree in Mechatronic Engineering

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ABSTRACT

Ongoing technological progress in measurement systems triggered the development of an innovative, hands-on teaching program to help students toward a fuller understanding of recent changes in the field. This paper presents a lab project that links theoretical principles with the practical issues of signal conditioning systems. This is accomplished in the context of a Master's Degree in Mechatronic Engineering, though the experience gained could be applied to other curricula. Students designed and tested a signal conditioning circuit in order to acquire and monitor the electrical activity generated by the heart. This lab project contains most of the circuits studied in lectures and presents a general methodology for the design of signal conditioning systems. Five years of lab project work was compiled, and with the help of students' feedback, we were able to evaluate both the improvement in their knowledge and in their motivation

Key Words: Measurement systems, signal conditioning, data acquisition, DAQ, ECG, LabVIEW

INTRODUCTION

Mechatronics is defined as "the interdisciplinary field of engineering dealing with the design of products whose function relies on the integration of mechanical and electronic components coor-

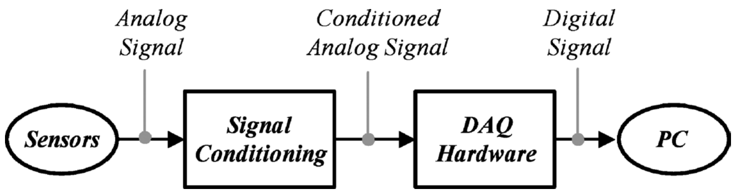

Figure 1. Typical block diagram of a basic measurement system.

dinated by a control architecture" [1]. Hands-on engineering experiments are needed in order to provide mechatronic students with the technical and research skills they will need as professional engineers. In a modern mechatronic measurement system, information is extracted from the environment using an appropriate sensor or sensors and the signals are then amplified to a suitable level so that they may be digitized and read by a data acquisition system.

In order to teach aspects of signal conditioning to mechatronic students, any experiment would require at least a single sensor whose output must be conditioning, data acquisition (DAQ) hardware and a computer to store and monitor the signal, as shown in Fig. 1.

The sensor converts a physical phenomenon into a measurable electrical signal. If the signal from the sensor is not suitable for the DAQ hardware it may be necessary to use a signal conditioning. In many cases the signal must be amplified and filtered. Also, isolation and linearization may be necessary. DAQ hardware is what usually interfaces between the analog conditioned signal and a PC. It could be in the form of modules that can be connected to the computer's ports or cards connected to slots in the motherboard. DAQ software is needed in order for the DAQ hardware to work with a PC.

The design of a signal conditioning circuit for the measurement of analog quantities typically poses difficult engineering challenges. Even a simple signal chain with a resistive sensor and an analog-to-digital converter (ADC) involves multiple issues that must be resolved before a valid measurement can be made.

To resolve these challenges the traditional learning model based only on lectures needs to be updated to incorporate real-world projects to facilitate students' critical thinking and problem solving skills while accomplishing the course objectives. Students need to get involved and take responsibility for their learning experience; and the instructor becomes a guide. The purpose of implementing this learning from a lab project (LP) is to motivate students to integrate and utilize knowledge rather than to re-involve students into the learning process after an extended period of inactive listening.

This paper is organized as follows. The next Section provides background on the educational literature, relevant literature on learning from lab projects and from lectures with integrated lab projects. The third Section provides a description of the course. The fourth Section is an overview of the lab project. The assessment of the course is included in the fifth Section. The student survey together with the instructors´ observations are presented in the following Section. Finally, conclusions are offered in the last Section.

BACKGROUND CONSIDERATIONS

The ability to conduct and design experiments is rated as one of the most desirable technical skills for engineering and engineering technology graduates [2], [3]. The National Science Foundation has reported that engineering education should include "integrative laboratory experiences that promote inquiry, relevance, and hands-on experience" [4].

In the context of higher education, integrative learning is not a new concept, as it has been advocated by educators for some time [5]. As reviewed by Huber and Hutchings [6], the core aim of integrative learning is for students to make connections across disciplinary boundaries and apply what they have learned to solve more complicated problems. One common integrative learning activity is to assign students to work on design projects [7], [8]. Another advantage of project-based learning is that it provides opportunities for students to develop their non-technical skills like problem solving, teamwork, and communication, all of which can be transferred to the workplace [9].

The implementation of learning from lectures with integrated lab projects is presented in several areas of instruction, such as power electronics [10], biomechatronic engineering [11], robotics for mechatronics engineering [12] or electronic instrumentation [13].

These educational premises essentially form the basis of our teaching philosophy for this ECG lab project. This topic is a well-established area of instruction; however, this work differs in two ways from other lab-based courses with ECG measurement. First, our course is not organized in the form of a series of well-defined but separable modules (i.e. unlike the ones seen in [5]). Secondly, we have not made use of commercially available student lab kits (e.g. [14], [15]).

DESCRIPTION OF THE COURSE

This lab project is part of the subject, Signal Conditioning Systems (SCS) which is included in the curriculum for the Master's Degree in Mechatronic and Micro-Mechatronic Systems (EU4M) [16]. It is a two-year European Master's program in which three European universities participate: HSKA Karlsruhe (Germany), ENSMM Besançon (France) and UNIOVI (Spain).

Identical lessons are presented at each institution during the first year of study to provide students with the same level of knowledge. The second year must be completed at one of the other two institutions. During the first year, course content includes Automation, Mechanics and Materials, and

Topic	Description	Lectures (hours)	Lab (hours)
I. INTRODUCTION	Introduction to Measurement Systems Static and Dynamic Characteristics of a Measurement System Calibration	1	-
II. AMPLIFICATION	Introduction Single-Ended vs. Differential Signals Basic Op Amp Configurations Special Amplifiers	4	-
III. FILTERING	Introduction Basic Filter Types Filter Specifications Filter Approximations Filter Topologies	2	-
IV. CONVERSIONS AND LINEARIZATION	Introduction Resistance-to-Voltage Converters V-I and I-V Converters V-F and F-V Converters Linearization	3	-
V. DATA ACQUISITION SOFTWARE (LabVIEW)	LabVIEW Environment SubVI Data Acquisition Structures Graphs and Charts Arrays and Clusters File I/O	-	10
Total hours		10	10

Table 1. Syllabus of the SCS course.

Electronics. During the second year course content includes Manufacturing, Micro-systems, Mechatronic Systems, Robotics, and Prototyping.

The course on SCS is scheduled in the second half of the first year within the Electronics module. It is a 3 credit course, equivalent to 10 hours of Lectures, 10 hours of Laboratory, 30 hours for Individual work and 35 hours of Teamwork. Table 1 summarizes the syllabus of the SCS course. The lecture hours are devoted to explaining the theoretical concepts of signal conditioning. The lab hours are devoted to explaining the LabVIEW software. During the individual work hours students must solve several theoretical exercises proposed/presented during lectures. Finally, students undertake a lab project during teamwork time. The number of students is between 15 and 20 grouped in teams of two, and where possible, one of them is a student of Mechanics and the other a student of electrical engineering or electronics.

After completing the SCS course a student should be able to:

- Understand the nature and characteristics of the signals to be measured.
- Be able to draw the measurements in the form of a block diagram.

- Explain the different approaches for designing a conditioning circuit.
- Select and design the right filter topology.
- Understand data acquisition principles and how to use a data acquisition board.
- Design a LabVIEW Virtual Instrument to monitor signals, and
- Promote collaborative work.

OVERVIEW OF LAB PROJECT

These guidelines are intended to assist the student with regards to the methodology that they should follow in the design of any measurement system. Thus, this lab project is organized into several activities with objectives, time limits, and assessment outcomes. The lecturers must check the satisfactory conclusion of each team activity before they can pass to the next activity.

The lab project consists of the acquisition, the conditioning and the monitoring of the electrical activity of the heart, captured over time by external electrodes attached to the human body. This application is selected because it includes many of the syllabus topics on the SCS course. From the students' point of view it is very motivating to obtain practical results with this kind of application. Fig. 2 shows the main idea of the proposed lab project. Students must design the signal condition circuit and a LabVIEW program to monitor the ECG signal on the computer. The data acquisition board is the National Instruments USB-6009.

Below is an overview of the activities carried out in the LP. A more detailed description of these activities and the course topics can be found in [17].

Activity 1: To understand the nature and characteristics of the signal to be measured

Time: 4 hours

The first step in designing any measurement system is to achieve a full understanding of the signal to be measured. Students are encouraged to search for information on the ECG signal in order to

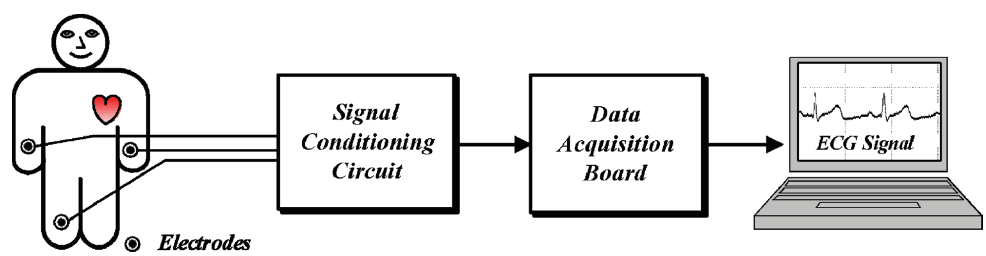

Figure 2. Set up of the proposed lab project.

learn the most noteworthy features (amplitude, bandwidth) and the most noteworthy problems (presence of biological interference, noise from environmental sources) [18].

Activity 2: To select the topology of the conditioning circuit

Time: 4 hours

Once students are familiar with the nature and characteristics of the ECG signal, the next step is to select the topology of the conditioning circuit. Students are encouraged to discuss the advantages and disadvantages of each alternative.

Because the ECG is a differential low level signal and there are common-mode interferences, the first stage is an instrumentation amplifier (IA). On the other hand a typical ADC full-scale voltage is approximately 2.5 V, which implies a gain factor of 500 (assuming a 5 mV input signal) so in order not to saturate the IA the total gain must be distributed between the IA and an additional gain amplifier. A standard clinical ECG application has a bandwidth of 0.05-100 Hz; therefore, a filter is required. It could be a band-pass filter or a low-pass filter cascaded to a high-pass filter however. Patient safety is an important issue and so galvanic isolation is mandatory.

Interferences usually manifest as common mode voltage *vc* across both terminals of the IA. Since *vc*, can be transformed by the amplifier into an interfering differential signal, it is desirable to minimize *vc* by attaching a third electrode to the patient. The most common and effective use of the third electrode is to connect it to a driven-right-leg circuit. Due to the fact that students have difficulty in understanding the driven-right-leg circuit it could be a good idea to discuss the original work relating to this technique in class [19].

Activity 3: Design and testing of the signal conditioning circuit

Time: 10 hours

During this activity students design and test their conditioning circuit. They are advised to test each block separately. The lab is equipped with an oscilloscope, a waveform generator, a power supply and a multimeter. The electrodes and active components are provided, however, students must buy the passive components according to their specific design. Special care should be taken in the selection of passive components to achieve good accuracy. Fig. 3 shows one possible result of this task.

Activity 4: To Design a LabVIEW Virtual Instrument to monitor the ECG signal

Time: 10 hours

The output signal of the condition circuit is connected to a computer by means of a commercial data acquisition board, NI USB-6009. Students must design a LabVIEW Virtual Instrument to monitor the ECG signal, calculate the heart rate and activate an alarm when the heart rate falls below

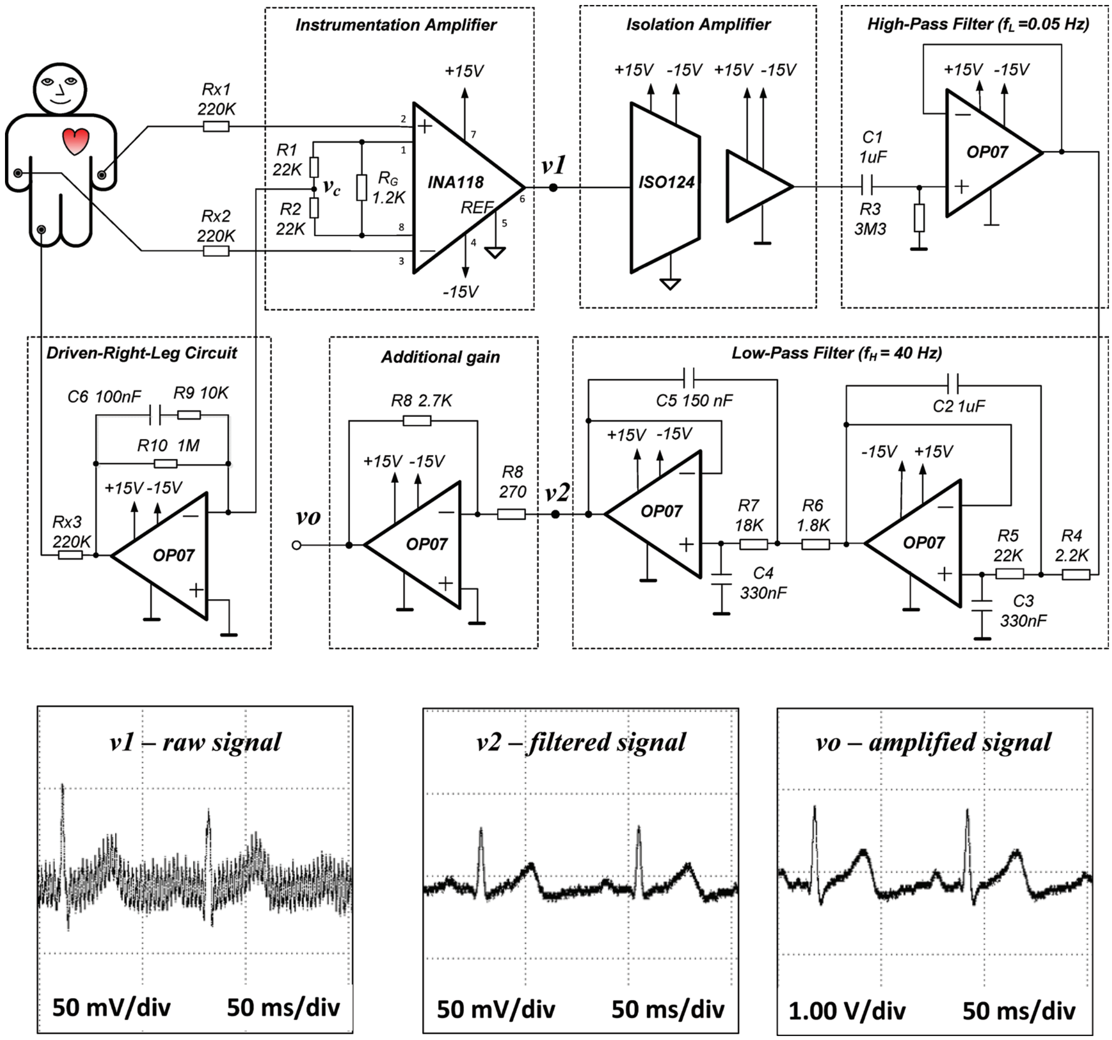

Figure 3. Electronic schematic and waveforms.

60 bpm (bradycardia) or rises above 100 (tachycardia). Using LabVIEW it is possible to acquire and monitor the ECG signal in a short time. To explain this software a LabVIEW 6-hour hands-on course is used [20]. Fig. 4 shows the results of activity 4.

Activity 5: Report the lab project

Time: 4 hours

The project does not end when everything is up and running. Every decision taken must be logical and documented so that the work can be understood and valued. Each team has a notebook

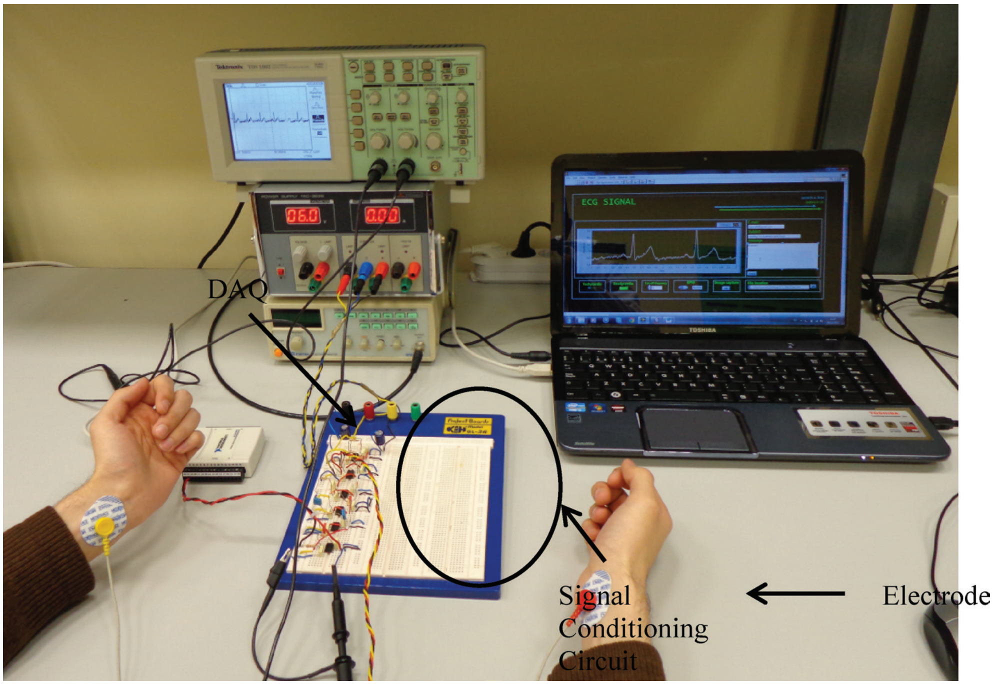

Figure 4. Activity 4: Lab Project setup showing the LabView program.

where team members jot down calculations and decisions taken in the course of the project. The notebook must be made available to the lecturer at any time so that he or she can check the progress of work whenever necessary.

COURSE ASSESSMENT

The goal of the assessment process was to assess the effectiveness of the course, identify problems, and then use this information to modify and improve the course - specifically in the area of improving the student learning experience. We needed to continually ask ourselves the following questions: "Are we teaching what we think we are teaching?" "Are students learning what they are supposed to be learning?"

With this aim, the final mark (*FM*) of the course is obtained by: $FM=0.1\cdot CA+0.2\cdot DE+0.7\cdot LP$, where:

CA is the mark of the class attendance.

DE is the mark obtained in the design exercises.

LP is the mark obtained in the evaluation of the lab project.

Class Attendance (CA)

Students have been assessed on the basis of whether they have participated actively during a lecture discussion period and whether they have been able to complete the in-class assignment during tutorials. We have found that this assessment component has encouraged students to attend classes and stay focused on the learning activities.

Design Exercises (DE)

The evaluation of the theory sessions was done with design exercises, one or two on each topic that the students solved at home and sent to their instructors using the Moodle platform. These exercises require students to design the circuitry including the component values. Students are also asked to justify their design considerations and write a brief white paper on their work. These exercises have been regarded as a formative assessment since our main goal has been to help students fine-tune their circuit design. Table 2 shows an example related to the amplification topic.

Lab Project (LP)

In the 2008-2009 course the evaluation of the *LP* was done beginning with a report of the *LP* that each team gave in to the instructor. This criterion did not reveal in detail the work done and if this work had been copied. During the following three courses the criteria of Table 3 were used. Criterion D is composed of a series of LabVIEW additional activities of which at least one must be chosen. Students are encouraged to address these additional activities with the help of the tutorials and examples provided by National Instruments.

Each team had to present the work in the laboratory and the instructor was able to question the teams on their work . The application of the criteria in Table 3 caused a significant improvement in the quality of the work done, but there was still not sufficient information to evaluate the competencies which the students should have acquired. In order to try to improve the evaluation of the *LP* it was decided to design a system of evaluation based on rubrics. Thus, from the 2012–2013

Design the signal conditioning circuit to measure the atmospheric pressure and the relative humidity using the sensors of this table. The sensors are connected to an ADC whose input range in between 0 V to 2.5 V. The power supply is a battery of 3 V. Find the minimum resolution of the ADC.

Variable	Range	Resolution	Reference
Pressure	0–8 psi	1 psi	Honeywell 24PC
Relative Humidity	0–100 % RH	2% RH	Honeywell HIH-3610

Table 2. Example of the design exercise to evaluate the amplification topic.

Criterion	Description	Mark (%)
A	Make a memory in which the decisions adopted and the calculations carried out are justified. It is suggested that said memory contain objectives, an introduction, hardware design, software design, conclusions, and references.	20
B	Mount on a breadboard the circuit of the ECG signal conditioning and test it using electrodes.	30
C	Create a program in LabVIEW that permits: ■ Display of the ECG continuously and stores it in a file for at least 60 s. ■ Calculation of heart rate. ■ Activation of an alarm if the heart rate for a number of consecutive cardiac cycles is less than 60 beats per minute (bradycardia) or above 100 beats per minute (tachycardia).	40
D	Additional activities using LabVIEW: • Generate a report in Word with patient data. • Send the report by email. • Control the application from a remote front panel. • Use a webcam to communicate with the patient. • Design the VI using a state machine. • Remove noise using the wavelet transform.	10

Table 3. Criteria used for the evaluation of the LP.

course the rubrics system of Table 4 was used. These rubrics have been carefully designed to assess the main competencies to be enhanced, to promote the application of theoretical concepts and to provide the students with an ability to propose solutions to problems and to enhance critical reasoning.

	3	2	1	0
Activity 1	The nature and the electrical characteristics of the signal are explained clearly.	The nature and the electrical characteristics of the signal are explained clearly but are incomplete.	The nature and the electrical characteristics of the signal are not explained clearly and are incomplete.	The nature and the electrical characteristics of the signal are not understood.
Activity 2	The topology of the conditioning circuit is correct and well justified.	The topology of the conditioning circuit is correct but not well justified.	The topology of the conditioning circuit is a little unclear.	The topology of the conditioning circuit is wrong.
Activity 3	The conditioning circuit is designed correctly and the tests are successful.	The conditioning circuit is designed correctly but sometimes there are problems with the test.	The conditioning circuit is designed correctly but there are always problems with the tests.	The conditioning circuit has design problems.
Activity 4	A full LabVIEW virtual instrument is designed and the tests are a success.	A basic LabVIEW virtual instrument is designed and the tests are a success.	A LabVIEW virtual instrument is designed but the tests aren´t a success.	The LabVIEW virtual instrument is not finished.
Activity 5	The report is presented in a neat, clear, organized fashion that is easy to read.	The report is presented in a neat, clear, organized fashion that is usually easy to read.	The report is presented in an organized fashion but may be hard to read at times.	The report appears sloppy and unorganized. It is hard to know what information goes together.

Table 4. Rubrics used to assess the activities of the LP.

Course	N	Mean	S.D.
2008–2009	10	7.2	0.79
2009–2010	14	7.3	0.65
2010–2011	12	7.4	0.78
2011–2012	15	7.5	0.70
2012–2013	14	7.8	0.64
2013–2014	17	8.0	0.64

Table 5. Course marks obtained over the last six years.

Table 5 shows the marks obtained by the students for the six years since the 2008–2009 course. Students fail if they get less than 5 marks out of 10. These marks are grouped in four intervals, which represent the grade given to the student. As can be seen in Table 5, the marks obtained improved as better defined systems of evaluation were introduced. The fact that the students had a greater knowledge of the LP having done it in previous years may have had an influence on the marks. Some students that do the Master's Degree work and study at the same time and so they are not able to finish the lab project in one year. This may result in their exchanging information with new students but, on the other hand, the design exercises are different every year.

RESULTS

To understand students' learning outcomes and experiences within the project-based curriculum, we assessed their perceptions, appraisals, and performance. At the end of the semester, all students completed a questionnaire developed by the teaching team. Information to be collected included students' perceived usefulness of the acquisition of specific skills; the problems that students encountered; resources that were difficult to access; their experience of working in teams; and the benefits of the curriculum. All evaluation items were evaluated on a 6-point Likert scale of 0–5 indicating degree of agreement. To ensure the validity of the measurement the Cronbach's alpha coefficient was obtained. The reliability of the measurement was reasonably acceptable ($\alpha = 0.933$).

As shown in Table 6, students improved their ability to apply knowledge acquired in class (4.43) and to more easily develop new projects (4.39). They agreed with the materials and documentation (4.36). The lab project was perceived to be effective in helping students to combine theory and practice and increase their interest in learning (4.30). Many of the students have indicated that they have gained a considerable amount of knowledge and hands-on experience in designing a

	Mean	S.D.
Rate your improvement in your ability to apply knowledge acquired in class	4.43	0.79
Rate your improvement in your ability to more easily develop new projects	4.39	0.65
Rate your satisfaction with the materials and documentation	4.36	0.78
Rate your satisfaction with the work done	4.30	0.70
Rate the evaluation of this course	4.23	0.64

Table 6. Student survey scores (N=17).

simple medical device like the ECG monitor. It also appears that their transferrable skills like problem solving and critical thinking have been improved through taking our course (4.23). These positive outcomes are consistent with what has been reported in literature reviews on integrative learning [21], [22]. The surveys also included the opportunity for students to leave comments, suggestions, etc. These comments were of great help. These comments and the solutions adopted are included in the Conclusion Section.

According to the above survey, students generally had a positive attitude toward the curriculum, and the results of the survey also reflected high appraisals that supported the effectiveness of the LP in this course. However, several problems and difficulties have been encountered:

1) The main problem detected was the difference in students' preparation prior to the start of the project. In the 2008-2009 and 2009-2010 courses students studied 'Electronic Instrumentation' in the first semester which meant that students with a mechanical profile could begin the SCS subject with knowledge of electronic circuits. In the 2010-2011 course EI was eliminated which forced the redesign of the SCS program. The most significant changes consisted in using the ideal model of the operational amplifier. The subject of filters was also simplified using for its design free computer programs like FilterLab or FilterPro.
2) The second important issue is the need to evaluate the complexity of the LP carefully. A complex LP will not improve the level of learning and students may become frustrated. If, on the other hand, a very easy task is set it will be easier for the instructor but it will lack the necessary ambition that a Master's project ought to have. The best way to be familiar with the problem of the LP is without doubt for the instructor to do the project previously as if he were a student noting down the difficulties encountered, the time spent and the components necessary etc. It is advisable to have a mounted prototype that can serve as a reference for students. The LP must permit the application of knowledge acquired in the theory classes. In this regard the measurement of biopotentials is very interesting since it requires significant preparation.

3) One of the most frequent issues that came up was that the LP was set too late, which forced a greater effort from the students at the end of the semester in parallel with other subject assignments. In order to solve this issue the LP was introduced at the beginning of the course and in each subject in the theoretical classes those aspects which were related to the LP were explained.
4) Another problem detected was that the numbers of hours dedicated to explaining the LabVIEW program (10 hours) were insufficient. This problem did not have an easy solution within the Master's Degree and for this reason we opted to propose a voluntary seminar outside of class hours. This seminar was very successful and has been repeated each year. In this seminar more advanced themes of LabVIEW are explained such as state machines, remote panels, communications, etc.
5) Some students seemed to have difficulty in identifying the error sources for the problems encountered during the design process. These students at first thought that circuit design work was like following a "cookbook recipe" with well-defined steps. They believed that their ECG device should work if they followed the circuit implementation steps, but they failed to realize that the process has many degrees of freedom that can affect the circuit's performance. In this respect two practical questions must be taken into account in order to obtain good results: a) the main source of interference is the power supply which gives rise to a common-mode voltage and in order to minimize its effect the so called right-leg circuit must be explained in detail. b) LabVIEW has a VI that simulates the ECG signal. Its use avoids having to connect the electrodes to the body while the program is being done in LabVIEW. Finally, the VI that simulates the ECG signal is replaced by the real ECG signal.
6) Although we allowed students to form groups as they wished, we still observed some conflicts as the course progressed. One group had the problem where one student dominated another to the point where the submissive student gradually adopted the role of an onlooker. The opposite trend was also seen in another group where an inactive student seemed to burden his group partner(s) with most of the lab project. Some team formation strategies should thus be incorporated into the next offering of this course, such as those discussed in [23].
7) The cost of components used in the LP is also an important consideration. Table 7 is an estimation of the cost of the components, approximately 50$. Except for the electrodes, the

Component	Reference	Quantity	Cost ($)
Instrumentation amplifier	INA118	1	9.23
Isolation amplifier	ISO124	1	15.91
Operational amplifiers	OP07	1	4.83
3-Lead ECG snap set lead wires	3M	1	21.85

Table 7. Cost of the components used on the LP.

rest of the components are in principle reusable. The integrated circuits are supplied to the students while the passive components are bought by the students according to their design. With this measure it is intended that the students make a more responsible use of the components.

CONCLUSIONS

A laboratory project carried out in the SCS subject within the Master's Degree in Mechatronics is described in this article. Throughout the six years the teaching methodology has been improved and difficulties posed by the students resolved. The subject syllabus has also undergone changes in content to adapt it to the different curriculum of the students. The assessment of the students obtained by means of surveys has always been positive which suggests that the work done has been worthwhile. Finally, teachers involved in this experience hope that their know-how, reflections, and results could be of use to others who would like to conduct this kind of lab project in the future.

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