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Integrative Learning through the Design of an Electrocardiogram Acquisition System

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***Abstract*— This paper presents an electrocardiogram acquisition system course design project for an upper year bioinstrumentation course. The objective of this design project is to provide students an opportunity for an integrative learning, enhancing their educational experience. Unlike similar electrocardiogram instrumentation projects, this project is based on a commercially available instrumentation amplifier enabling better systems-level thinking. The project is described along with observations made from our pilot implementation of the project. The initial offering of the project is considered a success with positive feedback from students. Recommendations for improvements are also discussed.**

Keywords – biomedical engineering, bioinstrumentation, education, electrocardiogram, electrocardiography, integrative learning

I. INTRODUCTION

BIOMEDICAL engineering is one of the most rapidly growing engineering fields. In the past decade, there has a been a number of new biomedical engineering programs, including those at the authors' institution (Carleton University's B.A.Sc. in Biomedical and Electrical Engineering, B.A.Sc. in Biomedical and Mechanical Engineering, and M.A.Sc. in Biomedical Engineering). The majority of these biomedical engineering programs, especially those with a focus on the electrical engineering related areas of biomedical engineering, have an upper year bioinstrumentation course, which typically includes a laboratory component. In the authors' institution, this course is *SYSC 4203 Bioinstrumentation and Signals*, which was delivered by the authors of this paper (lecturer A. Chan, teaching assistant S. Nizami) in the Fall 2010 session. Integrative learning experiences, as with many upper year engineering courses, are well-suited for such bioinstrumentation courses.

Integrative learning is promoted as an effective method of education that increases student engagement and better prepares them for real-world problem solving in the workplace [1]-[3]. Problem-based learning is well-suited in the integrative learning paradigm, especially in upper year engineering courses. Problem solving at this level should inherently require the integration of knowledge students have obtained in a broad range of topics. For a bioinstrumentation course students would be drawing on a number of subjects, including electronics, physiology, and signal processing. Yu *et al.* [1] presents an example of integrative learning through an electrocardiogram (ECG) design course. A shorter ECG design project (reported to be around 12 hours to complete the project) by the same author, *Electrocardiogram Amplifier Design Using Basic Electronic Parts*, can be found at IEEE Real World Engineering Projects (www.realworldengineering.org). In the shorter ECG design project, students design and evaluate a classic 3 op-amp instrumentation amplifier.

In this paper, we present a course design project in which our SYSC4203 students design an ECG acquisition system. We also share our experiences of the project's pilot implementation. A commercially available instrumentation amplifier is used in this project; hence, the design is performed at a higher level than the projects presented by Yu *et al.* Lower level details, such as the 3 op-amp configuration, is perhaps more relevant for other courses (e.g., electronics). The authors believe that abstraction to the higher level of design is more suitable to promote students' learning at the systems level.

II. ECG ACQUISITION SYSTEM DESIGN PROJECT

A. Project Overview

Student learning objectives of the ECG acquisition system design project include:

1. Identify important ECG signal characteristics,
2. Understand how different parts of an ECG acquisition system can influence the ECG signal,
3. Design and implement an ECG circuit, including drive-right leg, filtering and gain stages, and electrical isolation circuitry based on requirements, and
4. Troubleshoot and verify hardware implementation.

Students are instructed to design and implement an ECG acquisition system using a computer soundcard microphone input for analog-to-digital conversion. The recorded ECG should be of sufficient quality to compute the heart rate; that is, one can easily see waveforms in the signal associated with each heartbeat. Specific requirements for the ECG acquisition system are left to the student to allow for some flexibility in the design. For example, students may choose to follow recommendations for electrocardiographic equipment set by the American Heart Association [4]; other students may simplify the design with a narrow bandwidth to reduce motion artifact and high frequency noise, aiming to acquire an ECG solely for heart rate estimation. This flexibility enables students to potentially expand the project beyond the minimum requirements.

Students are also encouraged to learn some technical skills through the project, including schematic capture, bread boarding, and troubleshooting using measurement equipment (e.g., oscilloscopes, function generators, multimeters). As part of the project, students are asked to characterize the gain and common mode rejection ratio (CMRR) of their implementation and compare it against their design. Developing the methodology and testing procedures are left to the students; details on their methods are expected as part of their final report.

Unlike traditional laboratory experiences, which are well-defined such that students can execute them in a "recipe-like" format, this design project allows the students to drive the methodology. Consideration is given to provide some constraints to the design project to ensure the project can be accomplished within a reasonable timeframe and that the necessary resources are readily available.

B. *Design Framework*

Students are provided a basic design framework, which constrains the design problem and reduces the learning curve. The framework enables the design project to be completed in approximately 12 hours by a project group; students are working in groups of two.

Fig. 1 provides a system block diagram. The ECG bioamplifier is based on the AD620 (Analog Devices, Norwood MA), a low-cost instrumentation amplifier. The AD620 datasheet provides an implementation of an ECG bioamplifier (Fig. 41 in [5]); the implementation is modified slightly as shown in Fig. 1. The AD705J is an obsolete part and has been replaced with the OP97. Gain and filtering stages are left to the discretion of the students; LM741 operational amplifiers (National Semiconductors, Santa Clara, CA) are provided as active components for these stages. Analog-to-digital conversion is performed by a computer soundcard, which enables visualization and further analysis if desired (e.g., spectral analysis). For safety reasons, an ISO124 (Texas Instruments, Dallas TX) is employed. The system is powered by two 9 V batteries, which helps to ensure safety. One battery is used to supply power to the isolated portion of the circuit and another battery to supply power to the remainder of the circuit. While a single power supply could be used, this would further complicate the design, requiring further isolation for the power source. Table I provides a parts list that forms a project kits that is provided to each group. A picture of the kit is also provided in Fig. 2. Additional LM741 operational amplifiers are provided as needed. Students also have access to a variety of resistor values (5% tolerance; 1 kΩ to 10 MΩ) and capacitor values (10 pF to 220 nF).

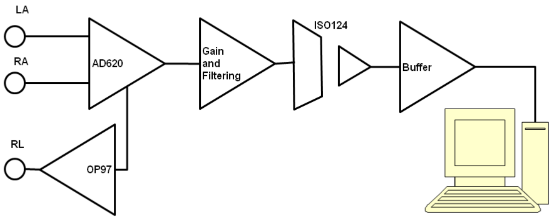

Fig. 1. ECG acquisition system block diagram.

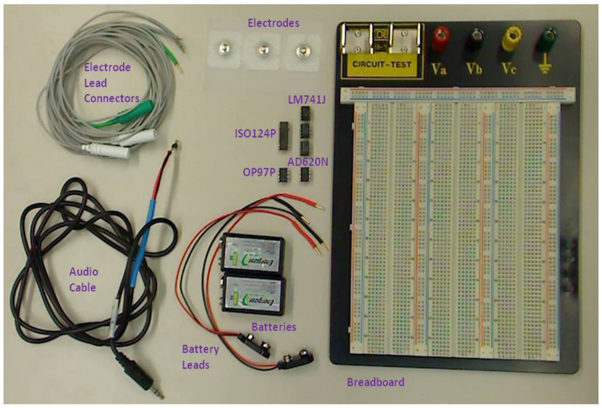

Fig. 2. Project kit items.

C. *Implementation*

Students were assigned this design project in the second half of a 13 week term (i.e., students had approximately 6 weeks to complete the project). Lecture materials pertaining to biopotential electrodes, amplifiers, and ECG had already been presented at the beginning of the term. The design project was run as an open laboratory; that is, there was no assigned laboratory time, except for their final system demonstrations, and students could access the laboratory

TABLE I
PROJECT KIT ITEMS

Item	Quantity	Description
AD620N	1	Low Drift, Low Power Instrumentation Amp (Analog Devices)
LM741J	3	Operational Amplifier (National Semiconductors)
OP97P	1	Low Power, High Precision Operational Amplifier (Analog Devices)
ISO124P	1	Precision Lowest-Cost Isolation Amplifier (Texas Instruments)
Breadboard	1	Breadboard
9 V battery	2	Battery
Battery leads	2	9 V battery connector and leads
Electrodes	3	Ag/AgCl disposable electrodes
Electrode lead connectors[a]	3	Electrode lead connectors with male SafeLead connectors
Audio cable	1	1/8" male audio connector with two wires

[a] Electrode leads with standard female button snap to female SafeLead connectors available in the laboratory.

resources at their convenience.

Students were required to submit a design schematic. This schematic was checked by the instructor for approval before implementation. Note that the design was mainly checked for safety and presentation (e.g., schematic is neatly drawn, parts are labeled) but obvious design errors were also noted. Major revisions in the design required resubmission of the schematic for another approval. Students were recommended to use CadSoft Eagle Light (www.cadsoft.de), which is a freeware schematic editor.

A tutorial on bread boarding was facilitated for the students, with emphasis on best practices (e.g., avoiding loose wires, using wire colors appropriately). Use on human subjects only proceeded after bench top testing and verification by an instructor.

At the end of the 6 weeks, students were to provide a demonstration of their system and submit a short written report the week after. The report consisted of four sub-sections:

1. Circuit design: explanation of the circuit and justification of design decisions,
2. Frequency response: explanation of the methodology used to measure the frequency response of the system (differential and common mode gain), a presentation of the results, and a discussion of the results with respect to the expected frequency response,
3. CMRR: explanation of the methodology used to measure the CMRR, presentation of the results, and a discussion of the results with respect to the expected CMRR and commercially available systems, and
4. ECG measurement: explanation of the methodology used to acquire a representative ECG, a presentation of the results, and a qualitative discussion of the quality of the measurement.

III. OBSERVATIONS

A course design project was a departure from conventional laboratory experiences. Conventional laboratory experiences provide students with clear step-by-step instructions. The ECG acquisition system design project defined a goal but with no mandated methodology; however, some constraints were provided (e.g., specific integrated circuits). Without being given clear instructions on how to proceed, students appeared to be hesitant or unsure of how to begin. This resulted in many students commencing the project with only 2 to 3 weeks remaining.

Three groups of the 17 groups provided some formal feedback. Table II provides their self-reporting regarding the time their group spent on the project. The same three groups either agreed or strongly agreed that the project met the learning objectives (5-point Likert scale), except for one group that disagreed with the second learning objective (*understand how different parts of an ECG acquisition system can influence the ECG signal*).

TABLE II
TIME TO COMPLETE DESIGN PROJECT (HOURS)

	Group 1	Group 2	Group 3
Design	1	1	2
Breadboarding	2	2	4
Debugging	1	8	2
Characterizing and evaluating	2	2	3
Report writing	1	2	3
Total	7	15	14

The project was instructive for students, such as learning how to read data sheets and how to layout a schematic. Interesting practical issues were encountered such as how to construct a virtual ground to provide a swing voltage from a single battery, buffering the ground, and the use of decoupling capacitors to stabilize the power. Many groups were also unable to interface the bioamplifier system to a computer through the computer soundcard's microphone. This was partly due to clipping of the signal caused by audio amplifier saturation or insufficient output drive. Some groups managed to resolve this issue by adjusting their circuit gain, as well as the soundcard gain (software controlled recording volume), and adding an appropriate buffer between the circuit output and the audio input. The remaining groups resorted to using a digital oscilloscope to observe and analyze their results. While students had the knowledge to understand the solutions to these various issues, many had not encountered such problems previously. The majority of their previous experiences involved simulations or more idealized setups (e.g., in a conventional laboratory experience a power supply would be used to provide a stable supply with a swing voltage).

The ECG signals were acquired in different manners. If the computer soundcard microphone input worked successfully then the ECG was recorded using Sound Recorder (Microsoft, Redmond WA, USA), or via Matlab (Natick MA, USA) using the data acquisition toolbox or the audio/video support functions (e.g., wavrecord). Further processing could be performed offline in Matlab, including plotting and spectral analysis.

Students had an opportunity to further develop their skills in hardware debugging. With conventional laboratories, students generally do not encounter hardware issues and if they do, would rarely resolve issues by themselves. In this design project, students were guided to test and debug each stage of their design to troubleshoot the completed system. This design project also increased students' appreciation for designing and implementing with debugging in mind. Good software practices (e.g., commenting, encapsulation) are well taught and encouraged in engineering but the same is not true for good hardware practices, although they share many similarities.

There was a great deal of satisfaction and feeling of accomplishment seen in the students when they were able to visualize an ECG. Indeed, one student noted that such design experiences provides a great deal of confidence for future design work.

IV. DISCUSSION

Students who were used to conventional laboratory experiences, which have well-defined step-by-step procedures, had difficulties adjusting to a more open-ended integrative learning design experience. The transition from a conventional laboratory experience to an integrative learning experience can be eased by breaking up the design project into multiple stages (e.g., designing, implementing, and testing the filter stages before any of the other stages), each with their own deadlines. In addition to aiding the students break down the problem into more manageable tasks, it provides an avenue for earlier feedback. One student suggested periodic design reviews with the entire class, which would enable students to learn from each other. A potential disadvantage is that all the designs may converge to a single design.

Dry (polarizable) electrodes will be utilized next year to increase simplicity. Dry electrodes are often associated with higher skin-electrode impedance than wet (non-polarizable) electrodes [6]; however, this can be mitigated through the use of a large electrode size. Simple tin cans (e.g., those used to preserve food) can serve as suitable electrodes, with users gripping an electrodes with each hand. A ground electrode can be incorporated by splitting the tin cans in two, such that the palm of the hands touch the electrodes that are inputs to the ECG bioamplifier, while the fingers touch the ground electrode.

The complexity of the project can be also expanded. The course that this project was offered through is *SYSC 4203 Bioinstrumentation and Signals*, which includes signal analyses. Next year's offering of this design project will also ask students to implement a heart rate estimation algorithm, with a simple graphical user interface. This further reinforces the systems level aspects of the design project. A high level language (e.g., Matlab) will simplify the implementation process. The project can also be expanded to include communication and teamwork skills, through increased emphasis on the report, design reviews, and presentations.

V. CONCLUSIONS

An integrative learning experience was introduced to a fourth year bioinstrumentation and signals course. As a first attempt, the design project was kept relatively simplistic and constrained (e.g., heart rate estimation was not included this year). As indicated, there are a number of refinements that can be made to improve this design project, which will be implemented in the next offering of this project. In addition, a more comprehensive evaluation of this project from an educational standpoint will also be performed; however, feedback from the students were very positive even from this initial offering of the project.

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