A Hands-On, System-Level Analog Electronics Course

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***Abstract*—This Innovative Practice Category, Work in Progress paper presents an undergraduate electronics course that aims to better allow students to see the application of analog electronics at the system level. System-level analog electronics design is lacking in many of today's curricula, with many students finding the use of operational amplifiers and negative feedback techniques in application sensitive engineering confusing. The purpose of this paper is to present curriculum that attempts to address this issue by exposing students to a more top-down (as opposed to bottom-up) approach towards analog electronics. In the process, two projects are used (one in power management, and another in bio-potential instrumentation) to create a hands-on environment where students can test and apply the concepts taught towards realizing systems that meet certain performance specifications.**

I. Introduction

As is the case at a number of universities, electrical engineering students at our university have traditionally been taught analog electronics from the bottom-up in a two course sequence on transistor level analysis and design. When in today's society students continually hear messages that speak towards all electronic systems one day becoming digital, it is not uncommon for the typical electrical engineering student taking analog electronics to lack much enthusiasm towards the course material [1]. Indeed, the typical student seldom hears anything being marketed as analog. To better allow students to see where analog electronics fit into their lives (and hopefully to increase student interest and motivation towards the field), we are proposing to modify the curriculum associated with the second course in the analog electronics sequence. We are proposing to structure the course such that it incorporates more system-level analog electronics design topics. In the process, analog systems relevant in today's portable electronics environment will be used as vehicles to expose students to application sensitive engineering.

From an employer and hiring perspective, we also believe that it is becoming ever more important for semiconductor companies to have engineers knowledgeable about what is going on in systems at the macro, high-level. When interviewing potential engineers in the hiring process, for instance, it is not uncommon for candidates to be asked *why* a particular component or block is in a system [R. Kiely, private communication. June 2018]. And because most things in a system have cascading effects, if one does not know the context in which a block is operating, one in all likelihood cannot unlock the system's full potential. One can make a fast analog-to-digital converter, but what good is it if an appropriate amplifier is not driving it? Having a curriculum where system-level topics are presented can also be of benefit to students who are not interested in integrated circuit design positions. For applications engineering, it is simply the nature of the job to need to understand the constraints of a particular system and to know what components and blocks work best in its context. In marketing, one needs to understand which performance metrics are *actually* important based on the components and blocks in a system. This, in turn helps in arriving at new product definitions. For sales, one can get an edge by having knowledge on which of the performance parameters matter most. And for team leaders, system level knowledge helps in deciding how and where to divert resources on a particular project.

Traditionally, the second course in the analog electronics sequence has used the inner, internal circuitry workings of an operational amplifier as a vehicle to teach such topics as differential amplifiers, feedback, and stability. While these topics are important and should be taught, we believe that the direction from which they are approached can be improved. That is, concentrating the course on the design of a high-performance operational amplifier (at the transistor level) placed in an isolated negative feedback configuration does not necessarily allow most students to see where analog electronics fit into their lives.

In the spirit of the demonstrations-based approach presented in [1] towards teaching electronics, our proposed curriculum attempts to expose students to differential amplifiers, feedback, and stability by building a couple of negative feedback-based *systems* that have relevance in today's portable electronics environment. The first half of the course will teach students what negative feedback is at the system level, and its significance towards achieving precision in system performance. The design and prototyping of a discrete linear regulator for a battery will serve as the hands-on

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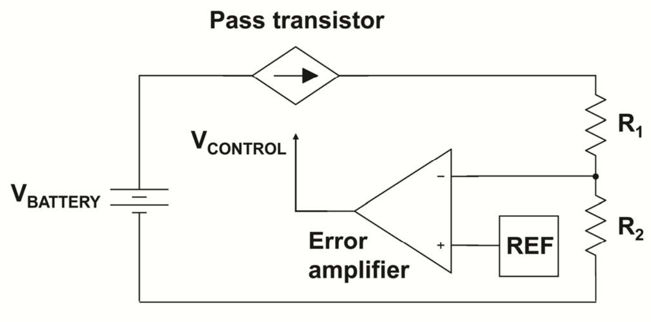

Figure 1. Linear voltage regulator system-level block diagram

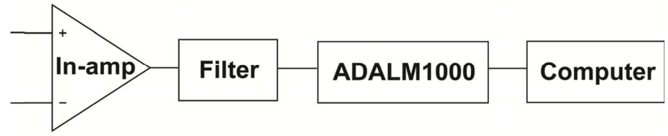

Figure 2. Bio-potential measurement system-level block diagram

component for this module. The second half of the course will involve the design and prototyping of a bio-potential signal chain, allowing students to not only investigate the effects of topology choice on overall system performance (e.g. 60Hz common-mode rejection, ability to tolerate differential electrode offset voltage), but to also gain exposure to interfacing an analog signal chain to a computer for subsequent digital backend processing. The linear regulator designed and prototyped earlier in the course will be used to regulate the supply voltages for the constituent amplifiers in the signal chain.

Specific goals of our proposed curriculum modifications include the following:

- Expose students to a more top-down (as opposed to bottom-up) system-level approach to analog electronics
- Provide system-level context to the significance of negative feedback by examining its effect in power management and signal chain systems, in contrast to the traditional examination of an operational amplifier in isolation
- Provide system-level context to the use of digital filtering algorithms for backend processing of sampled data, so that students may begin to appreciate the use and application of both analog and digital filters in signal chain systems
- Increase interest and motivation towards the general field of electronics by using the design and prototyping of a bio-potential signal chain as a vehicle with an interdisciplinary undertone. Hopefully in the process, this meets the growth in demand for electronics in fields such as biomedical engineering and the biological sciences

II. Development Of Hands-On Components Associated With Curriculum Modification

A. *Regulator (Power Management System)*

The first half of the course will use the basic block diagram associated with a linear voltage regulator to introduce the concept of negative feedback (Fig. 1). Initial discussions will use ideal voltage-controlled voltage source (VCVS) and voltage-controlled current source (VCCS) elements to model the error amplifier and pass transistor blocks, respectively. Subsequent analysis will vary the voltage gain and transconductance values for the VCVS and VCCS elements, respectively, to highlight the significance of loop gain on the overall effectiveness of the negative feedback loop. These discussions will be supplemented with SPICE simulations using the built-in "E" and "G" sources to model the VCVS and VCCS elements, respectively. Finally, stability will be investigated by examining the loop gain in the frequency domain, exposing students to the significance of phase and gain margin on system behavior.

The laboratories associated with this module guide students through the implementation of a discrete two-stage CMOS differential amplifier [2], in addition to a basic bandgap reference cell [3]. The project, in turn, involves the design and implementation of a linear voltage regulator (Fig. 1) that interfaces a differential amplifier, voltage reference, and pass transistor element. In the process, students will be expected to investigate the tradeoffs associated with the use of a NPN or PNP transistor for the pass transistor element (standard NPN regulator versus LDO PNP regulator), in addition to alternative topologies for the differential amplifier and corresponding effects on the stability and overall performance of the regulator.

Specific analog electronics-related goals of this module include:

- Expose students to the basics of differential amplifiers, and provide a system-level context for their application to realize a negative feedback loop that uses an error-amplifier (i.e. linear voltage regulator)
- Provide context to the significance of loop gain in a transistor-based system with negative feedback, and the impact on stability

B. *Bio-potential Measurement (Signal Chain System)*

The second half of the course will use the basic block diagram depicted in Fig. 2 to expose students to a mixed-signal design that incorporates both analog and digital subsystems. In contrast to the earlier power management

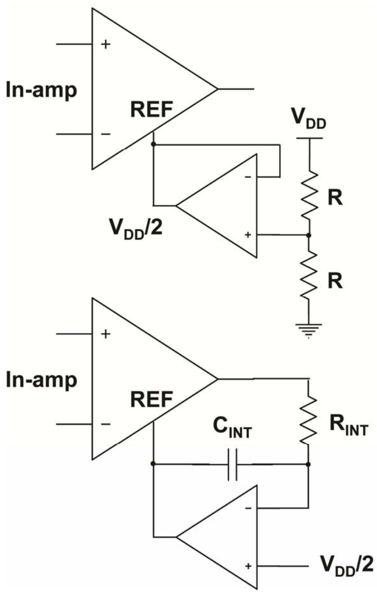

Figure 3. A couple of different topologies towards "centering" the DC bias associated with the in-amp output. The bottom structure uses an integrator in a negative feedback loop around the difference amplifier to reduce offset voltage effects and 1/f noise.

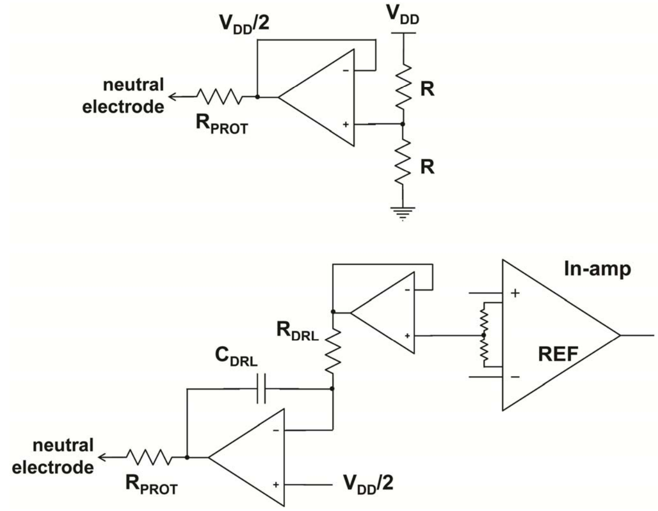

Figure 4. A couple of different topologies towards "driving" the neutral electrode fed back to the human body. The bottom structure uses a driven right leg circuit, which uses common-mode negative feedback to reduce the potential difference between human body and amplifier's common.

module (where operational amplifiers were viewed as differential amplifiers at the transistor-level), the second module will treat the operational amplifier as a "block" that can be used to perform appropriate signal conditioning towards the realization of a bio-potential signal chain system. This, in turn, will allow discussions pertaining to some of the pertinent non-idealities associated with operational amplifiers (e.g. offset voltage, finite gain-bandwidth product (GBW)), and the corresponding impact on the signal chain system. The bio-potential theme associated with this module was inspired by the electroencephalogram (EEG) front-end mixed-signal interface system described in [4]. In order to make the project associated with our proposed curriculum more open-ended so that students may better practice design skills (in addition to incorporating a more negative feedback theme), we will be adding content such that students investigate topology and architecture level decisions on the overall system performance of the bio-potential signal chain.

Example topology decisions that students will be asked to investigate include:

- Choice between an instrumentation amplifier (in-amp) realized using discrete operational amplifiers (OP90 [5], LT1079 [6]) versus an integrated circuit in-amp with better matching (AD620 [7]), and the impact on common-mode rejection ratio (CMRR) at 60Hz
- Use of AC-coupling networks to reduce the propagation of electrode and operational amplifier offset potentials in the signal chain [8]
- Use of an integrator in a negative feedback loop around the difference amplifier of the in-amp to reduce offset voltage effects and 1/f noise [9-10], as shown in Fig. 3
- Choice between standard neutral electrode or driven right leg circuit in a negative feedback loop and the impact on CMRR [11-13], as shown in Fig. 4

Students will be asked to investigate and decide among these choices to design and prototype a bio-potential measurement system (e.g. EEG, electrocardiogram (EKG/ECG), electromyogram (EMG)) that meets CMRR requirements set forth by the International Federation of Clinical Neurophysiology and/or American National Standard ANSI/AAMI, with and without complete electrode impedance imbalance [14]. The linear voltage regulator designed and prototyped in the first module of the course will serve to regulate the supply voltages for the constituent operational amplifiers associated with the signal chain.

An important aim associated with this module is to expose students to the application of basic digital filtering and signal processing algorithms towards the analysis of data obtained from the bio-potential front-end. In this spirit, students will use the active learning module ADALM1000 (Analog Devices, Inc.) to acquire and log signal data on a computer for backend processing in MATLAB. Students will be asked to import the data into MATLAB and write basic scripts towards additional filtering and analysis (e.g. spectrogram) for the purposes of deducing information. For an EEG-based system, for instance, the objective could be to identify points in time where the human body was relaxed with eyes closed, leading to noticeable alpha wave activity at ≈ 10Hz [15].

Specific analog electronics-related goals of this module include:

- Provide a system-level context towards comparing and contrasting general purpose, dual-supply operational amplifiers with offset voltages and GBW products in the mV and MHz ranges, respectively (e.g. LF347 [16]) versus precision, single-supply operational amplifiers more suitable for instrumentation with offset voltages and GBW products in the μV and kHz ranges, respectively (e.g. OP90 [5], LT1079 [6])
- Provide context to the distinction between and significance of differential- and common-mode gain, using CMRR 60Hz as a system-level design metric
- Provide context to the significance of loop gain in instrumentation and operational amplifier-based topologies with negative feedback, and the impact on stability

III. Student Survey and Comments

At the conclusion of the pilot version of the course offered Spring 2018 semester, a short student survey was conducted. The survey used Likert-style questions along with short answer questions to learn of students' understanding of the topics covered. Student responses were anonymous. Fig. 5 shows the data (mean ± standard error) for the Likert questions, where students were asked to rate from 1 to 5 how their level of understanding of a couple of topics had increased. The number 1 indicated that they had not understood the topic at all, and 5 indicated that they had completely understood the topic.

In addition, students were asked to list strengths and weaknesses associated with the course. The questions have been listed below, with select student responses having been provided for each:

Q1. What should the instructor start doing?

- "Talk about more applications of op amps. Perhaps you could have a project based on characterizing an operational/instrumentation amplifier. I found it useful learning different terms that are found on a data sheet."
- "Describe potential problems that one may face and how to resolve them."
- "Go a bit deeper into linear regulators."

Q2. What did you like about the course?

- "I like that we had to piece blocks together and look at circuits in a more system block level."
- "I liked the bio chain because it offered a few options on the kinds of signals we wanted to observe. Also hooking up electrode[s] is a cool way of making it away from just using a function generator. My knowledge of SPICE and design methods has increased substantially through the design projects 1 and 2."
- "I liked how the design projects were a culmination of all of the circuit classes that we have taken so far. The course overall has given me a better appreciation and understanding of the electronics that are used every day."

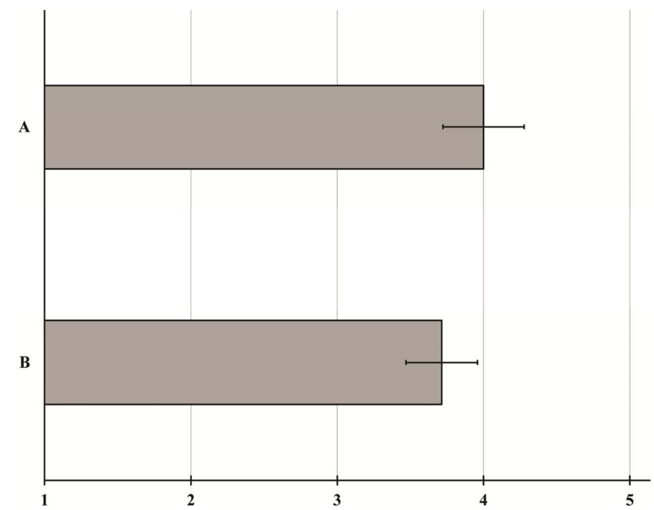

Figure 5. Student survey results of Likert-style questions: My level of understanding of the use of (**A**) negative feedback, (**B**) differential/operational amplifiers, in system-level analog electronics has increased.

IV. Conclusion

Overall, it appears that student feedback and comments express a high level of satisfaction with their experience in the pilot course. We are encouraged by the positive response of students. Based on the results of our survey (and the formal "student evaluation of teaching" conducted by the department, results of which had not been released at the time of submission of this paper), plus continuing research, improvements to the course will be implemented. In future offerings of the course, we also plan to conduct student surveys at the conclusion of each module (rather than solely at the conclusion of the semester) to monitor student learning as the semester progresses. Our hope is to create a learning experience where the interest level and enthusiasm of students towards electronics increases, in addition to exposing students to system-level analog electronics design and application sensitive engineering.

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