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A New Application-Oriented Electronic Circuits Course for non-Electrical Engineering Students Using Arduino and NI VirtualBench

Dr. Hooman Rashtian, University of California, Davis

Hooman Rashtian received the Ph.D. degree in Electrical and Computer Engineering from the University of British Columbia, Vancouver, BC, Canada in 2013 and the M.Sc. and B.Sc. degrees in Electrical Engineering from Isfahan University of Technology, Isfahan, Iran, in 2008, and 2006, respectively. He was a Postdoctoral Scholar at Davis MM-Wave Research Center (DMRC) at University of California, Davis from 2014 to 2016. Since July 2016, he has joined the Department of Electrical and Computer Engineering at University of California, Davis as a Lecturer with Potential Security of Employment (Teaching Professor). His teaching interests include circuit theory as well as analog, digital and RF electronic circuits and systems. His educational research interests include applying technology to design modern circuits courses and laboratories.

Mr. Jun Ouyang, University of California, Davis

Jun Ouyang received two bachelor degrees in Electrical Engineering and Computer Science from University of California, Davis, CA, United States. He worked as an IT professional prior to his college years. He is currently a Master's student at University of California, Davis and works on designing analog integrated circuits. As a development teaching assistant, he works on designing modern laboratory materials for undergraduate electrical engineering students. In his spare time, he enjoys working on automating solutions for physical problems using different programming languages.

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I. Introduction

Teaching circuits to non-electrical engineering students has always been a challenging task since many of these students find the circuit theory difficult, abstract and unrewarding. This can be partly associated with the fact that oftentimes the first circuit course that is offered to non-electrical engineering students, i.e. "*Circuits I*", is the same as the one offered to electrical engineering students. While in *Circuits I* students learn about the basic circuit theory, many of them especially those from engineering disciplines other than electrical engineering, may find the specific arrangement of the circuits elements in most of the circuits that they study, random and arbitrary. Consequently, they do not appreciate the importance and applications of the theory which is taught to them and thus lose their interest in circuits.

A good opportunity to win back students' interest in learning circuits, is the second circuit course which for non-electrical engineering students can be an introduction to electronic circuits and systems. In this research experiment, we have designed a new application-oriented course which provides non-electrical engineering students with insight in the application and role of circuits in larger systems. Considering that most of the non-electrical engineering students need to learn how to build circuits for instrumentation applications [1-6], the course is structured to be about different building blocks of a practical measurement system. The availability of Arduino-based boards such Teensy 3.2 which are extremely easy to work with, provides the opportunity to have the students work on the full chain of blocks in a sensor system and build a circuit that completes a meaningful task. Moreover, the adoption of National Instruments VirtualBench, facilitates a more efficient measurement experience in the laboratory.

II. Course Structure

Electronics is one of the major fields in electrical engineering which is mostly used in communication systems, computers, control systems and instrumentation systems. While the first two fields are mostly studied by electrical and computer engineers, every engineer is faced to work with electrical equipment and systems, designed for control and instrumentation purposes. Therefore, understanding electronic instrumentation systems to sense, amplify and process physical parameters in measurement applications, is important for non-electrical engineering students especially before they start working on their senior design projects.

In this course, students are introduced to the basics of electronic circuits and systems by first seeing a real-life measurement problem in the first lecture, followed by a discussion on how to synthesize a circuit that can solve that problem. The motivation for adopting this approach is to motivate the student and give them the understanding that circuit theory can be used to realize important goals in the projects related to their own engineering major. The specific example of the measurement problem introduced in the beginning of class may vary depending on the enrollment numbers from different engineering disciplines. For example, if the majority of the class is from mechanical engineering, a monitoring system for engine temperature may be discussed, while if biomedical engineering students have the highest enrollment number, an electrocardiogram system for monitoring heartbeat or a neural probe may be explained in the first lecture.

After students are introduced to the "big picture" of a measurement system through an application example, the general building blocks of a measurement system (Fig. 1) and the role of each block in the chain is discussed. Throughout the quarter, each of these building blocks are discussed in the lectures in the same sequence that they appear in this general block diagram and before the discussion about each different topic is started, this block diagram is re-emphasized, reminding the students, where in this chain the topic of discussion fits.

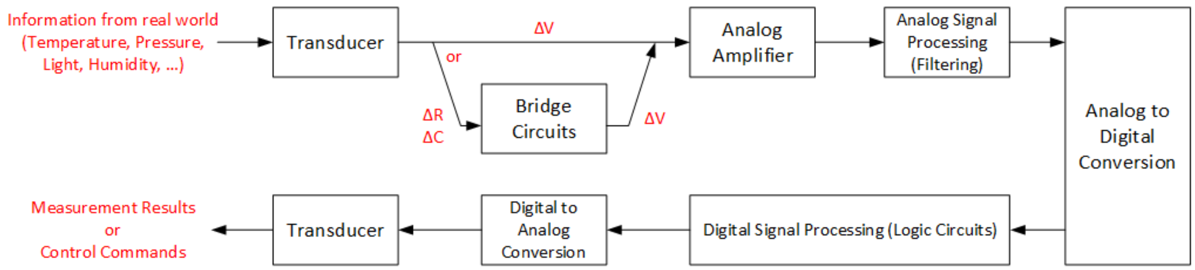


Figure 1: The general block diagram of an instrumentation system

In the laboratory, students work on individual building blocks of a light-meter in weekly lab sessions and at the end, they connect the different building blocks together as the final project of the course to build a system that can show the light intensity on scale of 0 to 9 on a 7-segment display. The availability of easy-to-use Arduino-based microcontroller boards such as Teensy 3.2 board [7] is essential here as using it gives the opportunity to implement the digital logic needed for controlling the 7-segment simply by using a software code. This would need an understanding of working with Karnaugh maps and Boolean logic while no advanced understanding of how to write microcontroller codes would be necessary. A short video which briefly describes the different building blocks of this light-meter and shows an implemented prototype of the project and how the overall circuit operates, is posted to the course webpage in the beginning of the quarter. As it will be explained in the section regarding digital circuits, to make sure that students also work with digital gates, a separate experiment which is not a part of the final project is added to the laboratory experiments in which students implement a threshold detector circuit using NAND gate ICs which turns on an LED when an input analog signal goes higher than a threshold.

In the laboratory, students perform their measurements using NI VirtualBench [8]. This modern software-based all-in-one instrument (Fig. 2) results in a very efficient and easy-to-debug measurement experience. This is particularly important when it comes to teaching circuits to students who have not worked with any measurement instruments before. In such cases, when conventional instruments are used in the laboratory, students are oftentimes overwhelmed by the fact that they need to learn how to work with several different instruments. However, this problem is alleviated when NI VirtualBecnh is used thanks to its very user-friendly interface. In this course, one laboratory session is dedicated to a tutorial on how to work with NI VirtualBench before students start working on actual laboratory experiments.

Figure 2: NI VirtualBench and its software interface

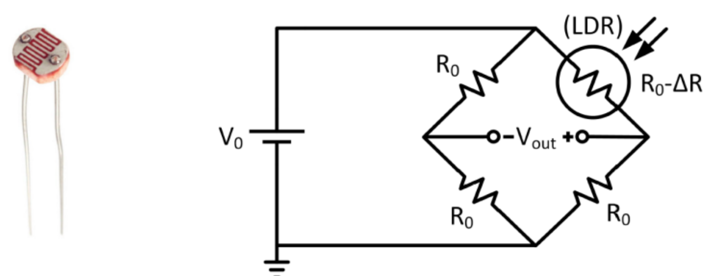
III. Course Syllabus and Laboratory Experiments

The following is a more detailed description of the topics covered in the course syllabus, application examples discussed in the lectures, and more details about the laboratory experiments. A summary of the topics discussed in this section can be found in Table 1 at the end of the section.

1) Transducers

Lectures: Transducers are the very first block of measurement systems which create an interface between the physical world and the realm of electronics. Two lectures are dedicated to an introduction to transducers and topics such as sensitivity, range, and Thevenin equivalent models of different sensors. It is also discussed how a change in a physical parameter can result in a change in the resistance and capacitance which forms the basis for understanding how resistive and capacitive sensors operate. The discussion on operation of resistive and capacitor sensors are immediately followed by examples about application of such sensors. For capacitive sensors, it is explained how by changing either the dielectric permittivity, parallel plate area or parallel plate spacing, a capacitive fluid gauge, an air pressure sensor or a car accelerometer can be implemented, respectively. For resistive sensors, the operation of a realistic piezoresistor sensor and its application in a pressure sensor is discussed.

Laboratory: Students work with a light-dependent resistor (LDR) shown in Fig. 3 (a) as an example of resistive sensors discussed in the lectures and they are asked to measure LDR's resistance using the NI VirtualBench digital multi-meter (DMM) under ambient light (R_0) and compare it to the resistance that they measure for the same sensor in dark (R_{dark}) and in abundant light (R_{amb}) when they shine light on the LDR using a flashlight.



(a) (b)

Figure 3: (a) light-dependent-resistor (LDR) (b) Wheatstone bridge light sensor circuit

2) Bridge Circuits

Lectures: The discussion on resistive and capacitive sensors is followed by the question that how a change in resistance or capacitance of a sensor can be processed by an electric circuit considering that electric signals are mainly in form of voltage or current signals. This leads to the discussion of Wheatstone bridge circuits and how they are used to convert the changes in resistance (ΔR) and capacitance (ΔC) of a transducer to a change in voltage (ΔV). The importance of linearity of the relationship between ΔV and ΔR or ΔC and the condition for having such a linear relationship is emphasized. Also, to show the range of voltages that can be obtained from bridge circuits, a typical piezoresistor sensor is used in a resistive Wheatstone bridge which results in an output voltage in the range of hundreds of microvolts.

Laboratory: Students are given the instructions to use the LDR sensor they worked with before, within a Wheatstone bridge with resistor values equal to the number they have read for LDR's resistance in ambient light, i.e., R_0 (Fig. 3 (b)). They are then asked to record the output voltage of the Wheatstone bridge under ambient light, abundant light and in dark and compare it to the values predicted by the linear equation discussed in the lectures. Since this circuit is a part of the final project, students are asked to keep their prototype circuits in their breadboards to be connected to the next blocks of the light-meter system.

3) Amplifiers and Op-amp Circuits

Lectures: By showing the students that the voltage that is obtained from a bridge circuit using a typical transducer mentioned, is usually very small (hundreds of microvolts for the piezoresistor example in the previous section), the discussion for the need for a sub-block that processes and magnifies the output signal of a bridge circuit is initiated. Before proceeding to amplifier circuits, the application of a cantilever to the pizeoresistor sensor discussed before, is studied as a mechanical solution for amplifying the pressure that is applied to the sensor which in turn results in a larger voltage at the output of the sensor and eventually the Wheatstone bridge circuit connected to it. Electronic amplifier are then introduced as alternative way of amplifying the output signal of sensors. Moreover, it is specified that since information can be processed faster and easier in electrical domain, electrical amplifiers are superior to their counterparts in other domains.

The rest of the lectures on this part of the course cover classic operational amplifiers followed by their applications in an instrumentation systems. More lecture time is spent on the difference amplifier and its applications for noise rejection in an electrocardiogram system and for sensing deviations from a nominal value in a temperature monitoring system are studied through examples. Most importantly, application of the difference amplifier for differential measurement such as for amplifying the output signal of Wheatstone bridges is elaborated. This discussion is followed by studying the loading effect and application of buffer amplifiers to solve this problem. In the case of Wheatstone bridges, two solutions is proposed to provide isolation between the bridge and the differential amplifier stage; first adding buffer amplifiers, and second using the instrumentation amplifiers. Finally, the non-ideal effects of op-amps as well as applications of op-amps for other analog signal processing such as integrating and differentiating is overviewed.

Laboratory: Two lab sessions are dedicated to op-amp amplifiers. In the first week, students implement inverting and noninverting amplifiers. In the inverting amplifier, the values of resistors are selected such that the 50-Ω resistance coming from function generator of NI VirtualBench loads the circuit. Students are given a hint about the internal resistance of practical voltage sources, and are asked to justify the discrepancy between the gain they calculated in their pre-labs and their measured values. Then they are asked to use a buffer amplifier between the function generator and the inverting amplifier which helps them to understand the practical importance of buffer amplifiers.

The second week's experiments are about implementing summing and difference amplifiers. For the difference amplifier, the values of resistors are again chosen such that the circuit is loaded by the 50-Ω internal resistance of NI VirtualBench function generator. However, this time instead of adding a buffer amplifier, students are asked to increase the resistance values of resistors in their circuits while keeping the ratio of them constant such that the gain of their amplifier do not vary. This technique would serve as an alternative solution to the loading problem that students may later use when connecting the difference amplifier to the Wheatstone bridge in their final project. Students are again asked to keep the difference amplifier circuit in their breadboards to be used in the final project.

4) Filter Circuits

Lectures: After studying analog amplification, filtering is introduced as the second type of analog signal (information) processing. Since students are to use filters, mainly for eliminating noise and interference in a measurement system, this part is started with an example about filtering a 60-Hz interference caused by nearby power utility lines in a telephone system. Although this specific example is not in the context of a measurement application, but it provides students with intuition about what an interference signal is and how it may corrupt the information which are being processed by an electronic circuits and/or system. The lectures continues with analysis of passive and active low-pass, high-pass, band-pass and band-reject filters. Another important application that students see in the lectures, is about low-pass filtering of power supply noise by adding a capacitor on the supply terminals of op-amps. Bode diagrams and their benefit in predicting the behavior of more complicated filter circuits is also discussed.

Laboratory: Students work on obtaining the frequency response and plotting the Bode diagrams for passive low-pass, high-pass, band-pass and band-reject as well as an active band-pass filter over two laboratory sessions held in two consecutive weeks. The application of low-pass filters for removing the power supply noise is included in the laboratory manual which helps the students observe the reduction of the noise of the output signal of their amplifiers when a capacitor is added to the power supply terminals of the op-amp(s). Students are asked to keep the passive low-pass filter they have implemented in their breadboards for future use in the final project.

5) Analog to Digital Conversion (ADC)

Lectures: The lectures are started by bringing students' attention to the point that physical signals have an analog nature (as they can take any value) and are continuous over time. This is followed by picturing the advantages of converting analog signals to digital signals. In particular the superior immunity of digital signals to noise and possibility of having more complex signal processing in digital domain is discussed. This is then followed by a discussion on sample-and-hold circuits and how such circuits divide the range of analog signals into discrete levels before they are applied to analog-to-digital converters. The study of the details of analog-to-digital circuits is postponed until the end of the course as it needs an understanding of digital combinational and sequential circuits. Finally, an introduction to binary numbers and binary arithmetic is covered in the lectures.

Laboratory: Students work with the analog-to-digital converter of the Arduino-based Teensy 3.2 board (Fig. 4). Since students do not have any knowledge about digital circuits at this point through the course, the application of such an easy-to-use microcontroller is crucial here to give the students a sense of the difference between analog and digital signals and how an analog signal can be digitized and be represented by binary numbers. Due to the lack of enough lecture time, the coding of the Arduino is not covered. Instead, a pre-written code which programs the Teensy board to act as a 3-bit ADC is uploaded to all the Arduinos used by the students and they are asked to apply a 0.2 to 3V (with increments of 0.4V) analog signal as the input signal and record the voltages that they read at the digital output pins and eventually, report the corresponding 3-bit binary number for each of the increments in the input analog signal. A modified version of this ADC is also used in the final project of the course.

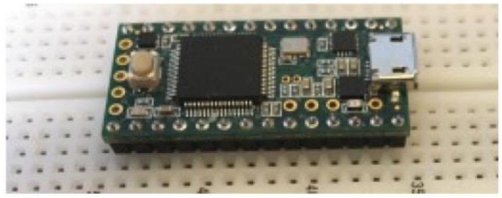


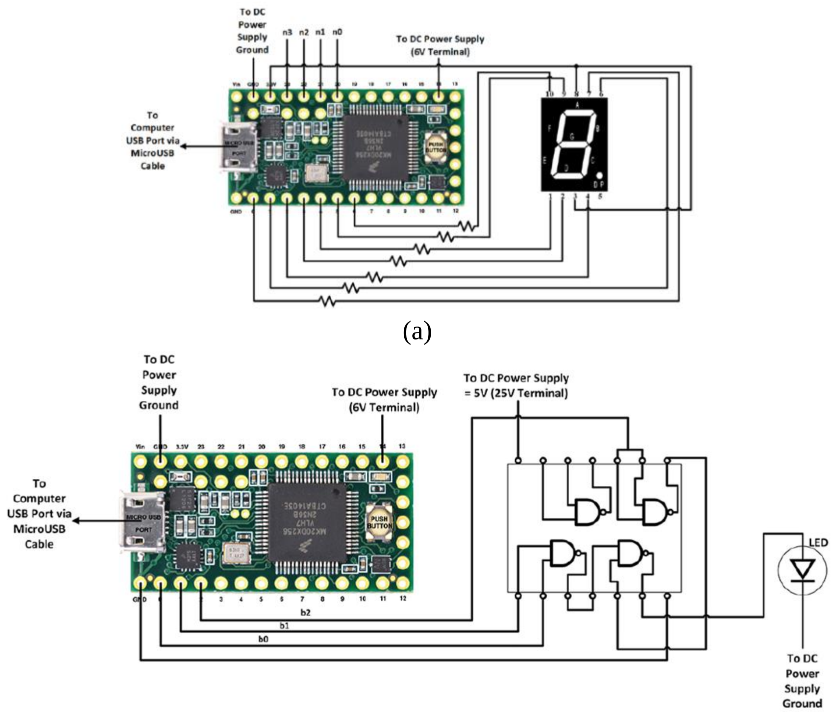
Figure 4: Teensy 3.2 board placement in a breadboard.

6) Digital Logic Circuits

Classic combinational and sequential logic circuits are studied in this part of the course. Topics such as basics of Boolean algebra and simplification of them using Karnaugh maps are covered. Digital displays are also discussed in the context of a measurement application to display the final result after analog and digital processing of the physical quantity of interest is completed. The 7-segment displays are studied in detail and it is discussed how to build the Karnaugh maps for synthesizing digital circuits for controlling each of the segments of the 7-segment display. As for the sequential circuits, different types of flip-flops, state diagrams and counter circuits are among the covered topics.

Laboratory: Two lab sessions are dedicated to digital logic circuits. At the end of these two lab sessions, students should be able to develop the right Boolean expressions for the input signals of a 7-segment digital display. They then add these expressions into a pre-written code which programs the Teensy 3.2 board. A simple introduction about using the right syntax for entering the obtained Boolean expressions from Karnaugh maps into the Arduino program is necessary here. They are also instructed on how to connect the output signals of the Teensy 3.2 board to the 7-segment digital display using current-limiting resistors (Fig. 5 (a)). Students then apply the same analog signal that they worked with in the experiment on ADCs as the input of the circuit and they observe that the number displayed on the 7-segment display goes up from 0 to 9 when the analog input voltage is increased from 0.2V to 3V. It should be noted here that to have students practice working with 4-variable Karnaugh maps, the Teensy board's ADC is pre-programmed to be a 4-bit ADC in this experiment. This circuit is also used as a part of the final project of the course.

To make sure that students understand both software and hardware implementation of digital logic, another experiment is assigned in which after converting the analog signal to a digital signal, instead of processing the digital signal by programing the Arduino, students apply the digital signal to a gate-level circuit implemented using a NAND IC which is designed to be a "threshold detector". The output of this NAND IC is connected to a light-emitting-diode (LED) which turns on only if the value of the input analog signal is higher than a threshold. The schematic for the threshold circuit is shown in Fig. 5 (b).



(b)

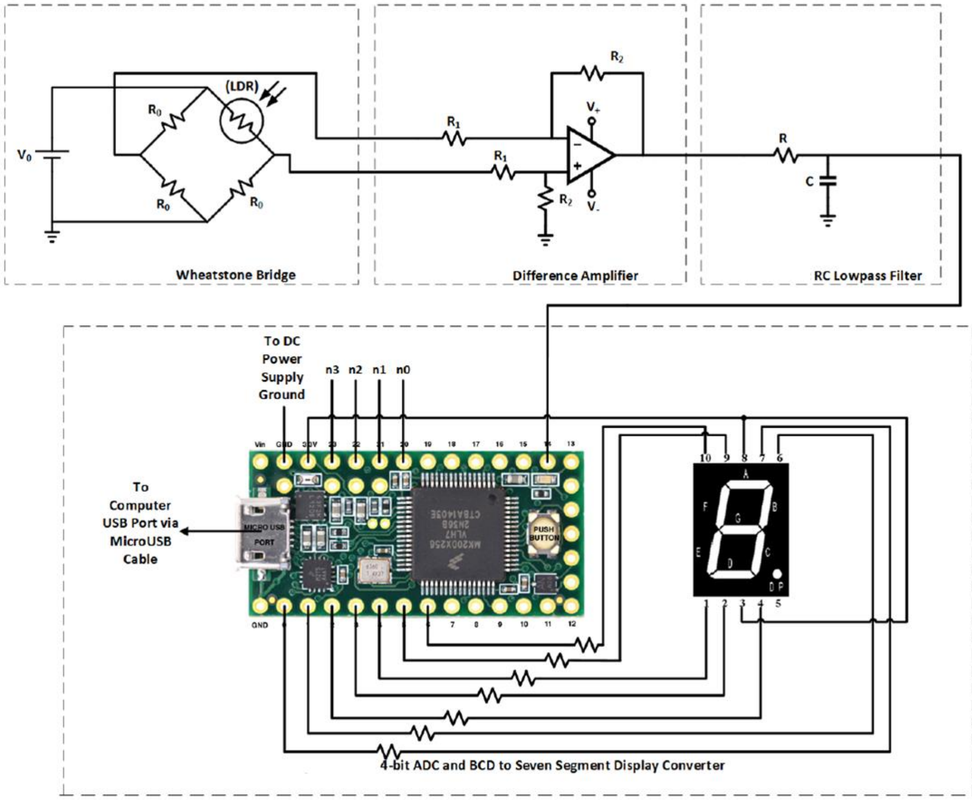
Figure 5: (a) Analog to binary-coded-decimal circuit (b) Threshold detector circuit using Teensy board's ADC and a NAND IC

7) Digital-to-Analog (DAC) Circuits:

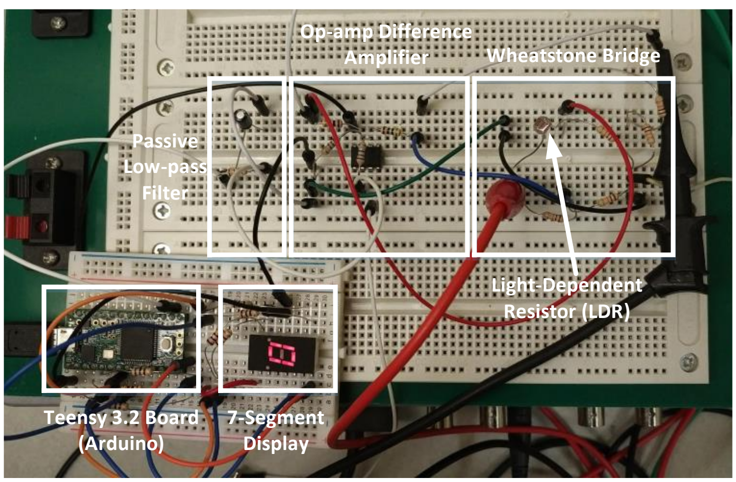
At the end of the course, it is explained for students that after finishing the digital signal processing, the results should be either displayed by using a transducer such as an LED (which converts the signal from electrical domain to light) or used as a control command for adjusting the deviations of the measured parameter from a reference value. In the latter case, there is usually a need for converting the digital signal back to analog domain. Simple ADC circuits such as R-2R op-amp based ADC circuit are introduced. Moreover, it is shown how DAC circuits can be used together with binary counters to implement ADC circuits.

8) Final Project:

In the final lab session, students connect the circuits they have constructed throughout the quarter to build a light sensor (Fig. 6) which can show light intensity in scale of 0 to 9 where 0 is assigned to ambient light and 9 to the case that a flashlight is brought close to the sensor. The main challenge for students is to address the problem of loading of the Wheatstone bridge by the difference amplifier. It is left for them to decide how they want to solve this problem and any solution including using buffer amplifiers, increasing the size of the resistors in the difference amplifier or even using an instrumentation amplifier is considered as an acceptable solution.



(a)



(b)

Figure 6: (a) Schematic and (b) photo of a prototype of the final project

Table 1: Summary of the proposed course syllabus, key application examples and laboratory experiments

Lecture Topics	**Key Application Examples in Lectures**	**Lab Experiments**
	Transducers	
- *Different Sensor Types* - *Resistive and Capacitive Sensors* - *Sensitivity, Range and Thevenin Model of Sensors*	- *Capacitive sensors: fluid gauges, air pressure sensors, car accelerometers* - *Resistive Sensors: Pressure sensor using piezoresistive sensors*	*Characterizing a Light-Dependent-Resistor (LDR) (0.5 session)*
	Bridge Circuits	
- *Resistive and Capacitve Wheatstone Bridge Circuits* - *Linearity Requirement*	- *Wheatstone bridge with a piezoresistive sensor resulting in μV range voltages*	*Wheatstone bridge incorporating a Light-Dependent-Resistor (LDR) (0.5 session)*
	Analog Amplifiers	
- *Operational amplifier* - *Negative feedback* - *Inverting, noninverting and buffer amplifiers* - *Summing, difference and instrumentation amplifiers* - *Op-amp non-idealities*	- *Cantilever as an example of mechanical amplification* - *Using buffer amplifiers to solve loading effect in a Wheatstone bridge circuit* - *Difference amplifier: noise rejection in electrocardiogram systems* - *Difference Amplifier: sensing deviations from a reference value in temperature monitoring systems* - *Difference Amplifier: differential measurement*	- *Inverting, noninverting and buffer amplifiers (1 session)* - *Summing and difference amplifier (1 session)*
	Analog Filters	
- *Low-pass, high-pass, band-pass and band-reject passive and active filters* - *Bode diagrams*	- *Filtering a 60-Hz interference caused by nearby power utility lines in a telephone transmission system* - *Low-pass filtering of power supply noise by adding a capacitor on the supply terminals of op-amps.*	- *Passive filters (1 session)* - *Active filters (1 session)*
	Analog-to-Digital Conversion	
- *Analog vs. Digital* - *Sample & Hold Circuit* - *Binary Numbers* - *Binary Arithmetic*	- *Robustness of digital signals to noise* - *Numerical example of conversion of an analog signal to a digital one at periodic intervals*	*Working with a 3-bit ADC programmed in a Teensy 3.2 board (0.5 session)*
	Digital Logic Circuits	
- *Boolean Algebra* - *Digital Gates* - *Combinational Circuits and Karnaugh Maps* - *Flip-Flops* - *Sequential Circuits and State Diagrams*	- *Digital displays: LEDs and 7-segments* - *Counter Circuits*	- *Threshold detector circuit using NAND ICs (0.5 session)* - *Seven-segment digital display control by programming Teensy 3.2 board (1 session)*
	Digital-to-Analog Conversion	
- *R-2R DAC Circuits* - *ADC circuits using DAC circuits and binary counters*	*N/A*	*N/A*

IV. Comparison with the Syllabus of the Second Circuit Course for Electrical Engineering Students

The proposed syllabus has significant differences with the syllabus which is usually offered to electrical engineering students. For electrical engineering students, the second circuit course focuses on more advanced circuit theories such as circuit analysis using Laplace transform, Fourier series and two-port network theory while covering the analog part of the course proposed in this work, i.e., operational amplifiers and analog filters. In addition to these theories, analysis of three-phase circuits and higher-order filters such as Butterworth and/or Chebyshev filters may be covered for electrical engineering students in their second circuit course. The digital circuits are usually studied in a dedicated course in electrical engineering and is not usually included in the syllabus of circuit courses.

V. Assessment:

To study the effectiveness of the proposed syllabus on increasing students' motivation in learning circuits, students in Fall Quarter 2016 were asked to participate in a research study. The study consisted of a 5-10 minute voluntary survey with 9 five-point Likert scale questions on students' experiences completing the final laboratory project of the course. Students were informed that no identifying information would be collected about the participants and that the instructor would not know which students chose to participate in the survey and thus there would not be any impact on their grade for participating or opting out of the study. The statements in the performed survey are as shown in Table 2:

Table 2: Statements in the voluntary survey

Statement 1	*The circuit applications included in the lectures helped me understand the importance and applications of the circuit theories that I had learned in "Circuits I"*
Statement 2	*The connection of each of the topics covered in the lectures to the next and the previous topic was very clear*
Statement 3	*There was a close connection between the lectures and the lab experiments*
Statement 4	*Working with the laboratory instrument (National Instruments VirtualBench) was straightforward*
Statement 5	*The final lab project helped me understand the theory presented in the lectures better*
Statement 6	*The final lab project provided me with the "big picture" on how small circuits are connected together to build a larger system*
Statement 7	*The idea of the lab experiments being smaller parts of a larger project made more motivated in the laboratory*
Statement 8	*The applications of topics covered in the course were made clear through the lecture examples, laboratory experiments as well as the final project*
Statement 9	*This course made me more interested in learning circuits comparing to "Circuits I"*

A summary of the survey responses is tabulated in Table. 3 and the distribution of responses is illustrated in Fig. 7. As shown in Table 3, the sample means ranged from 3.84 to 4.84, which strongly suggests that most of the students were satisfied with the course structure. A brief study of the solid bars in Fig. 7 provides additional support for the same conclusion: the combined responses of "Agree" and "Strongly Agree" exceeded 90% on six of the statements and they exceeded 80% on all of the statements.

VI. Future Work:

Although the assessment results show a strong support for the proposed syllabus, more work is needed to verify its effectiveness and its appropriateness of course's coverage. Fortunately, this curriculum has been adopted by other ECE faculty in the department who have agreed to run the same study at the end of their classes. This will provide us with more study samples and it also verifies if there is any dependency between the achieved outcomes and different teaching styles of different instructors. As a future work, stakeholders other than current students of the course such as instructors of subsequent courses and students who have completed subsequent courses are to be surveyed.

Table 3: Survey Responses and Statistics

Statement	Response					Statistics		
	5 Strongly Agree	4 Agree	3 Neutral	2 Disagree	1 Strongly Disagree	Total	Mean	Std. Dev.
1	42	13	1	0	0	56	4.73	0.49
2	37	17	2	0	0	56	4.63	0.56
3	48	8	0	0	0	56	4.86	0.35
4	13	32	2	7	2	56	3.84	1.04
5	31	20	5	0	0	56	4.46	0.66
6	48	7	1	0	0	56	4.84	0.42
7	20	27	8	0	0	55	4.22	0.69
8	38	11	7	0	0	56	4.55	0.71
9	45	9	1	0	1	56	4.73	0.67

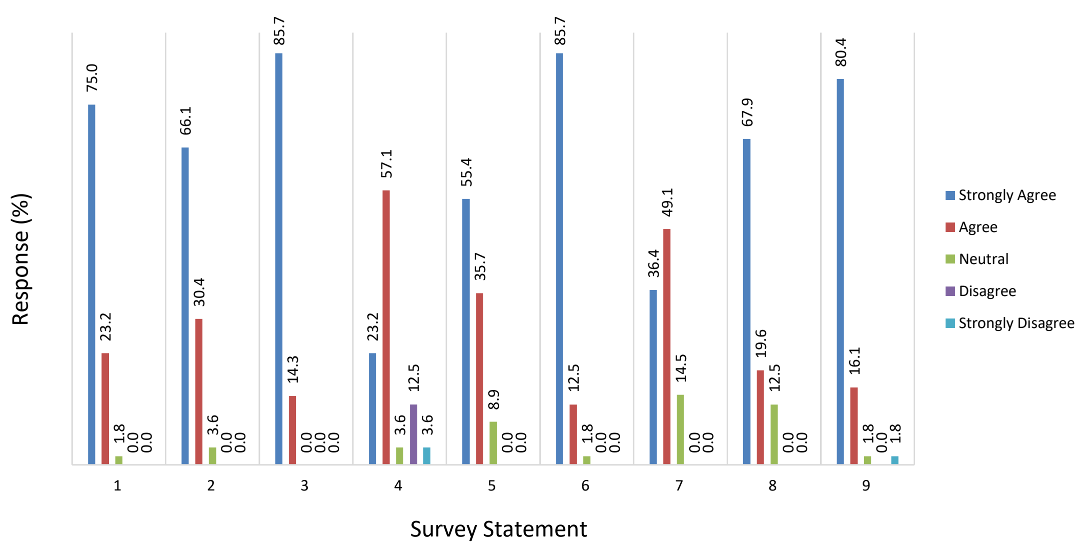


Figure 7: Response Percentage by Survey Statement

In terms of the syllabus, due to the popularity of using Arduino boards in senior design projects for non-electrical engineering students, it seems that including the coding and programming of such microcontrollers in the lectures would prepare the students for their senior design projects better. Considering that non-electrical engineering students rarely implement sequential circuits using flip-flops, reducing the lecture time on sequential circuits and adding Arduino programming instead could be a viable solution for improving the quality of the course in future.

VII. Conclusion:

An application-oriented electronic circuit course for non-electrical engineering students is presented. The course covers different building blocks of an instrumentation system in the same sequence that they appear in the system. In the weekly laboratory sessions, students implement these building blocks and at the end they connect different building blocks together to implement a full system. Implementing the full system in the lab is only possible due to the availability of Arduino-based microcontrollers which provide the chance to implement digital functionalities that would be very difficult to realize if only digital gates and/or flip-flops are to be used. Using NI VirtualBench also provides a more efficient measurement experience for students which in turn helps them to spend less time on debugging and more time on completing their designs. Based on the performed survey, it is shown that students show more interest in learning circuits if they see the applications of what they are taught right after the theory is explained.

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