Application of Portable Data Acquisition Tools and Virtual Instruments in an Upper-Level Biomedical Instrumentation Laboratory Course

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Abstract

Portable data acquisition hardware and virtual instrument software provide students with means to build and test circuitry outside of the confines of traditional benchtop laboratories. Such tools have been used effectively to complement historically lecture-based courses (e.g., circuit theory; signals & systems) with hands-on material without incurring commensurate scheduling burdens related to the use of physical laboratory space. Portable resources also promote flexible time management for students who have busy schedules because they can work in their homes or in communal learning spaces. While these data acquisition tools and their accompanying parts kits have proved useful in courses that address introductory circuit designs, they have not been broadly applied in upper-level courses that address more specialized circuitry, e.g., in biomedical instrumentation and measurement contexts.

This paper summarizes experiences from the Fall 2017 and Fall 2018 utilization of Digilent Analog Discovery 2 units and the bundled Waveforms 2015 software in a senior/graduate-level biomedical instrumentation course. Scripted laboratories addressed Analog Discovery 2 tutorials, bioamplifier fundamentals, analog filters, biomedical electrodes, and pulse plethysmographs. Each student utilized these portable tools to address their course design project – a wearable electrocardiograph with a Bluetooth Low Energy link to a cell phone. Student performance was assessed relative to learning objectives specified for the scripted laboratories and the course design project. Pre/post-project surveys were also employed to gauge student self-perceptions of learning in specific technical areas germane to biomedical instrumentation. Student feedback and summative assessments indicate that Analog Discovery 2 toolsets are an effective, arguably enjoyable, resource when applied in such an upper-level course, as they help students to meet learning objectives and gain technical proficiency without adding an undue burden to the learning process.

I. Introduction

A. Benefits of Portable Data Acquisition Tools

Since the early 2000s, portable data acquisition hardware and accompanying virtual instruments have become available that offer students and members of the makerspace community capabilities to build/test circuitry and create/acquire signals outside of the confines of more traditional laboratories that employ static benchtop equipment. These toolsets include the National Instrument ELVIS [1] (LabVIEW [2]), myDAQ [3], and myRio [4] platforms; the Rensselaer Polytechnic Institute Mobile Studio Project tools [5, 6] (along with RPI's project partners); the Virginia Tech Lab-in-a-Box (LiaB) materials [7, 8], the Digilent Electronics Explorer [9] and Analog Discovery [10, 11] products, and the Kansas State University Rapid Analysis and Signal Conditioning Laboratory (RASCL) toolkit [12-18]. The benefits of such tools are clear, as long as they are effectively implemented. These virtual instruments and portable hardware can facilitate learning experiences that complement traditional lecture courses without generating scheduling challenges for those that manage limited physical benchtop laboratory spaces. Further, students and faculty have more freedom to schedule hands-on sessions, and they experience flexibility in terms of preferred study and assessment venues.

These data acquisition hardware tools and parts kits, along with their accompanying virtual instrumentation software, are becoming broadly applied in earlier circuit theory courses and later linear systems courses. However, they have not yet been largely applied in more advanced courses that may utilize specialized circuitry, such as courses that address control systems, biomedical instrumentation, mechatronics, etc. The work summarized in this paper is a follow-on to earlier work at Kansas State University (KSU), where Rapid Analysis and Signal Conditioning Laboratory (RASCL) units that incorporated National Instruments myDAQ tools were applied in a biomedical instrumentation course context [13, 14]. In this case, the authors present early lessons learned from the Fall 2017 and Fall 2018 application of Digilent Analog Discovery 2 units to a similar set of hands-on biomedical instrumentation learning experiences.

B. Paper Contents
Section II provides a brief overview of the capabilities of the Digilent Analog Discovery 2 platform in light of the needs of a typical biomedical instrumentation course. The laboratory experiences offered to the students and their respective learning objectives are discussed briefly in Section III. Section IV then presents student products for the various scripted laboratories, student performance results with regard to laboratory learning objectives, self-reported perceptions of these learning experiences from the students' viewpoints, and a short collection of other lessons learned when applying Digilent Analog Discovery 2 in an upper-level biomedical instrumentation laboratory.

II. Background

A. ECE 773 – Theory & Techniques of Bioinstrumentation

The course, *ECE 773 – Bioinstrumentation Design Laboratory* (1 credit hour), is a required laboratory design course for KSU Electrical Engineering (EE) seniors enrolled in the Bioengineering Option. This course is a co-requisite to a lecture course, *ECE 772 – Theory & Techniques of Bioinstrumentation* (2 credit hours), and the 3-credit course pair is available to upper-level students in non-EE curricula. These courses address biomedical sensors, analog/digital instrumentation, signals, computer-based data acquisition, biosignal processing, medical imaging, medical image processing, and other related topics. ECE 773 has also been a target course to demonstrate the utility of USB-based, portable data acquisition tools developed at KSU [12-16].

B. Digilent Analog Discovery 2 (AD2) Unit

The Digilent Analog Discovery 2 (AD2) hardware unit [10] and parts kit [19] are pictured in Figure 1. This hardware mimics the collective toolset available on a traditional instrumentation bench by providing the combined functionality of a power supply, waveform generator, multimeter, oscilloscope, network analyzer, spectrum analyzer, data logger, and more in a small hardware package with physical dimensions that are approximately 3.25″ × 3.25″ × 0.75″. Channel connectivity is illustrated in Figure 2, and more detailed specifications are available on the company web site [11]. This hardware unit connects to a personal computer, laptop, or tablet via a USB connection, and a `Waveforms` app [20] provides a suite of virtual instruments that control various components of the overall instrumentation set and support signal visualization. The accompanying Digilent analog parts kit contains a small breadboard, a collection of passive components (resistors, capacitors, transistors, and diodes), sensors, a collection of chips (op-amps, regulators, and converters), lead wires, and a screwdriver. At the time this manuscript is written, pricing for verified students is about the price of a textbook: U.S. $229 for the combined set – the AD2 unit and parts kit, which are normally $279 and $55, respectively.

Figure 1. Digilent Analog Discovery 2 unit with wires, USB cable, and parts kit.

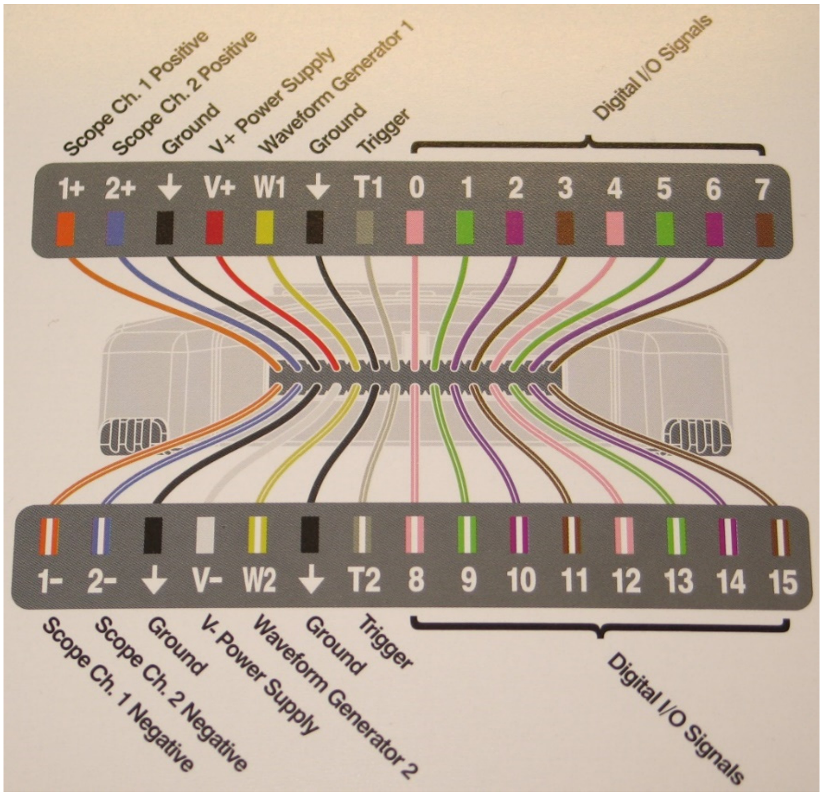


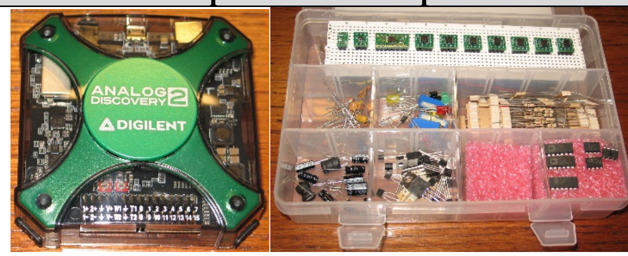
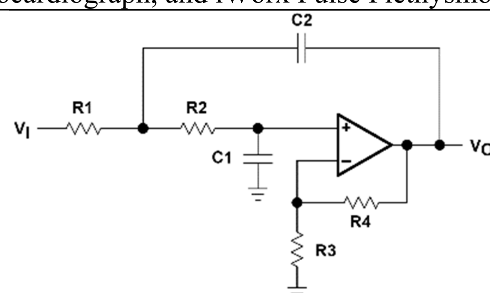
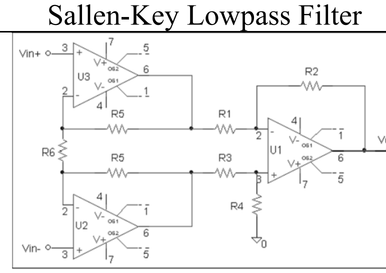
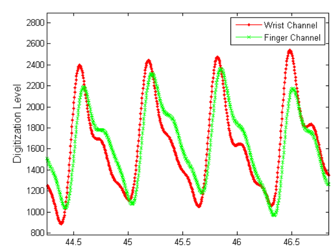
Figure 2. Digilent Analog Discovery 2 connections.

III. Methods

A. Laboratory Experiences

The Fall 2017 and Fall 2018 ECE 773 laboratory experiences are enumerated in Table 1 and described in more detail in the text that follows Table 1. Although the students used the AD2 units for all circuit excitations, input/output signal visualizations, and data storage, each fall class met in a traditional, eight-bench instrumentation laboratory so that the instructor and teaching assistant would have simultaneous access to all students during that weekly 3-hour segment. The first session was dedicated to a set of AD2 tutorials that Digilent publishes online [21], and the four subsequent sessions addressed various concepts related to biomedical instrumentation. These subsequent laboratories addressed bioamplifer fundamentals [22], active lowpass filters [13], biomedical electrodes [13, 14], and photoplethysmographs. Facets of some of these laboratories have been described in prior publications because these learning experiences had been previously used as test cases for earlier portable instrumentation developed by KSU faculty in collaboration with faculty at East Carolina University [13-15]. These five scripted laboratories were followed by a wearable electrocardiograph (ECG) project that incorporated elements of the prior labs and offered a significant design component. While students also used the AD2 units during this ECG project, the project itself is not described here because (a) the first instantiation of the project for Fall 2017 has already been described in detail in an ASEE 2018 paper [23] and (b) each student employed the AD2 functionality in an individual way. The second instantiation of the project is described in an ASEE 2019 manuscript accepted for publication [24].

Table 1. Fall 2017 and Fall 2018 laboratory experiences that employed Analog Discovery 2 units for circuit excitation and signal acquisition/visualization.

Laboratory Experience	Representative Graphic
Lab 1 – Getting Started with the Analog Discovery 2 The goal of this session is to introduce the student to functionality supported by the Analog Discovery 2 unit and the Waveforms 2015 companion software [10].	 Digilent Analog Discovery 2 Unit and Parts Kit
Lab 2 – Bioamplifier Fundamentals This laboratory session addresses basic instrumentation skills needed to analyze the properties of a commercial two-channel bioamplifier.	 iWorx ETH-255 Bioamplifier, CB Sciences C-ISO-255 Electrocardiograph, and iWorx Pulse Plethysmograph
Lab 3 – Active Lowpass Filters The goal of this laboratory is to familiarize students with two configurations for second-order active lowpass filters: Sallen-Key and Multiple-Feedback (MFB).	 Sallen-Key Lowpass Filter
Lab 4 – Biomedical Electrodes This laboratory introduces students to instrumentation amplifiers and their practical use in biomedical electrode applications.	 Instrumentation Amplifier Layout for ECG Version 1
Lab 5 – Photoplethysmography (Fall 2018 only) Students design, implement, and evaluate a simple photoplethysmograph, which uses light to measure blood volume changes and can serve as a simple heart rate monitor.	 Photoplethysmograms

The following text provides general descriptions of these laboratory sessions as a supplement to the information in Table 1. Learning objectives for the individual laboratories are described in the following section and listed in the accompanying Table 2.

- **Lab 1 – Getting Started with the Analog Discovery 2**
  Each student completes the following AD2 tutorials:
  - *WaveForms 2015 Windows Installation* (optional – for personal computers/laptops)
  - *Getting Started With Analog Discovery 2 (Windows)*
  - *Calibration*
  - *Using the Oscilloscope* (optional - requires a BNC adapter board for the scope leads)
  - *Using the Waveform Generator*
  - *Using the Spectrum Analyzer*
  - *Using the Power Supplies*
  - *Data Logger*

  A student records start/stop times for each tutorial so that instructors can gauge typical completion times, and interim results are copied and pasted to a Microsoft Word file that serves as a session diary. This diary also contains anecdotal student thoughts/observations.
- **Lab 2 – Bioamplifier Fundamentals**
  Each student analyzes properties of a commercial two-channel bioamplifier: input/output offsets, gain, frequency response, AC & DC coupling, and analog filters (highpass, lowpass, and bandpass). A piezoelectric pulse plethysmograph and a 3-lead electrocardiograph provide illustrative signals and spectra germane to this class of bioamplifier.
- **Lab 3 – Active Lowpass Filters**
  Students compare time- and frequency-domain data acquired for two types of second-order, active lowpass filters (Sallen Key and multiple-feedback filters) with their corresponding transfer functions as predicted by theory and PSpice simulations. Excitation waveforms, oscilloscope functionality, and waveform analyses are provided with the Digilent AD2 and Waveforms 2015 toolset.
- **Lab 4 – Biomedical Electrodes**
  Each student builds instrumentation-amplifier-based circuitry to acquire electrocardiograms (ECGs) and electro-oculograms (EOGs). The design element for this laboratory involves the configuration of cascades of suitable filters to remove unwanted signal components while keeping the desired signals intact. The exercise utilizes the Digilent AD2 and Waveforms 2015 toolset to provide circuit power and to acquire and visualize signals.
- **Lab 5 – Photoplethysmograph**
  Each student builds a photoplethysmograph comprised of a current source that drives a red LED, an adapter that houses the LED and a photodiode on either side of the finger, a current-to-voltage converter, and a final gain stage.

B. Laboratory Learning Objectives

Each of the five scripted laboratories offered formal learning objectives, phrased in the manner, “Upon completion of this laboratory, the student should be able to …” These learning objectives are listed in Table 2 along with their corresponding point values (PVs). These point values were assigned based on an accumulation of points from the various laboratory protocols that supported each learning objective. The parameters “F17 Avg” and “F18 Avg” are computed as the average score for the entire laboratory section divided by the full point value (PV) for that learning objective. The parameters “F17 Met” and “F18 Met” are integers that indicate the number of students out of 8 in each section that met a learning objective. The final two columns in Table 2 identify similar metrics but for the aggregate two-semester grouping of students. These numbers are discussed briefly in *Section IIIB*.

Table 2. Learning objectives for scripted laboratories. (PV = Point Value; # Met = # of Students that Met the Learning Objective out of 8 (F17) or 8 (F18)).

"Upon completion of this laboratory, the student should be able to …"							
Learning Objectives: Lab 1 – Getting Started with the Analog Discovery 2	**PV**	**F17 Avg**	**F17 Met**	**F18 Avg**	**F18 Met**	**F17/18 Avg**	**F17/18 Met**
• Install the Digilent Waveforms 2015 software and drivers on their computer of choice (Windows, Mac, Linux)	2	2	8	2	8	2	16
• Utilize the basic features of the Analog Discovery 2 unit and the Waveforms 2015 companion software	6	6	8	6	8	2	16
• Explain how these features can be applied to help create and test biomedical instrumentation.	2	2	8	2	8	2	16
Learning Objectives: Lab 2 – Bioamplifier Fundamentals	**PV**	**F17 Avg**	**F17 Met**	**F18 Avg**	**F18 Met**	**F17/18 Avg**	**F17/18 Met**
• Provide circuit excitation waveforms with WF2015 and an AD2	3	2.38	7	2.5	8	2.44	15
• Acquire signals with the WF2015 oscilloscope and an AD2	4	2.75	7	3.13	8	2.94	15
• Measure signal amplitude	1	1	8	1	8	1	16
• Quantify signal timing	3	1.75	7	2.25	8	2	15
• Operate a two-channel bioamplifier	2	2	8	1.94	8	1.97	16
• Describe the roles of input/output offsets	2.5	2.5	8	2.38	8	2.44	16
• Explain the concept of gain	0.5	0.5	8	0.44	8	0.47	16
• Describe an amplifier's frequency response	4	2.5	8	3	8	2.75	16
• Compare AC versus DC coupling	2	1.38	8	1.5	8	1.44	16
• State the role of a highpass filter	2	1.25	8	1.5	8	1.375	16
• State the role of a lowpass filter	2	1.25	8	1.5	8	1.375	16
• Describe biomedical signal behavior and spectral content	5	3	7	3.69	8	3.345	16
Learning Objectives: Lab 3 – Active Lowpass Filters	**PV**	**F17 Avg**	**F17 Met**	**F18 Avg**	**F18 Met**	**F17/18 Avg**	**F17/18 Met**
• Calculate and plot theoretical transfer function behavior, $\|H(\omega)\|$, for active second-order Sallen-Key and MFB Butterworth filters	2	2	8	2	8	2	16
• Describe the behavior of a lowpass filter given input sinusoids at different frequencies	3	1.88	6	1.5	8	1.69	14
• Simulate time- and frequency-domain filter behavior in PSpice	1	1	8	1	8	1	16
• Explain the character of an output signal from a lowpass filter given an input square wave	5	3.63	7	3.63	8	3.63	15
• Construct, debug, and evaluate active, second-order lowpass filters	2	1.69	7	2.00	8	1.845	15
• Utilize the basic functionality of a Digilent Analog Discovery 2 (AD2) computer-based							

data acquisition system and the companion Digilent Waveforms 2015 (WF2015) virtual instrument software to							
– supply sine/square waves to a circuit under test,	1	0.88	7	1	8	0.94	15
– display time-domain signals at various circuit locations, and	1	0.88	7	1	8	0.94	15
– perform peak-to-peak voltage measurements	1	1	8	1	8	1	16
• Compare experimental transfer function data to the theoretical and simulated $H(\omega)$ curves	1	0.81	7	1	8	0.905	15
• Compare the architectural design and frequency-domain performance of Sallen-Key versus MFB lowpass filters	1	0.69	6	0.69	7	0.69	15
• Discuss the effects of op amp quality on filter performance	2	1.38	6	2	8	1.69	14
• Archive the results in an electronic format	1	1	8	1	8	1	16
Learning Objectives: Lab 4 – Biomedical Electrodes	**PV**	**F17 Avg**	**F17 Met**	**F18 Avg**	**F18 Met**	**F17/18 Avg**	**F17/18 Met**
• Place ECG and EOG electrodes at meaningful locations on the human body	2	1.88	7	1.88	7	1.88	16
• Construct circuitry to acquire differential ECGs and EOGs with body-worn electrodes	6	5.63	7	5.63	7	5.63	16
• Design filter circuitry to remove unwanted ECG and EOG signal components while retaining desired components	4	3.13	8	3.75	8	3.44	16
• State the performance differences between a difference-amplifier configuration and an instrumentation amplifier configuration with a right-leg drive circuit	2	1.88	8	1.75	7	1.815	15
• Acquire and analyze signals using the Digilent AD2 and WF2015 toolset	2	2	8	1.88	8	1.94	16
• Describe the features of time-domain ECGs and EOGs	2	1.56	8	1.625	8	1.5925	16
• Relate time-domain features of ECGs and EOGs to their corresponding frequency spectra	3	2.13	8	2.13	7	2.13	15
• Compare characteristics of ECGs and EOGs in the time and frequency domains	3	2.75	8	2.875	7	2.8125	15
• Archive the results in an electronic format	1	1	8	1	8	1	16
Learning Objectives: Lab 5 – Photoplethysmograph (F18 Only)	**PV**	**F17 Avg**	**F17 Met**	**F18 Avg**	**F18 Met**	**F17/18 Avg**	**F17/18 Met**
• Build a finger adapter to house the LED and photodiode	1	N/A	N/A	0.88	8	0.88	8
• Implement a current source circuit	3	N/A	N/A	2.88	8	2.88	8
• Implement a photodiode sensor circuit	4	N/A	N/A	3.63	8	3.63	8
• Design a supplemental gain stage	4	N/A	N/A	3.69	8	3.69	8
• Evaluate the integrated circuit	2	N/A	N/A	2	8	2	8
• Identify mitigation options for ambient light	1	N/A	N/A	1	8	1	8

C. Surveys and Other Assessment Mechanisms

Formal surveys directly related to the use of AD2 units in these scripted laboratories were not offered to students, but students did complete pre/post-project surveys affiliated with the follow-on wearable ECG design. These surveys, described in detail in an ASEE 2018 paper [23], asked students to rate their understanding of each of a number of topics according to a five-point Likert scale, where a "1" indicated no understanding and a "5" indicated full understanding. Selected survey responses that relate to AD2 use will be briefly presented in *Section IIIC* below. Additionally, the instructors gathered other pieces of anecdotal information during the Fall 2017 and Fall 2018 course offerings – these thoughts will be laid out in *Section IIID*.

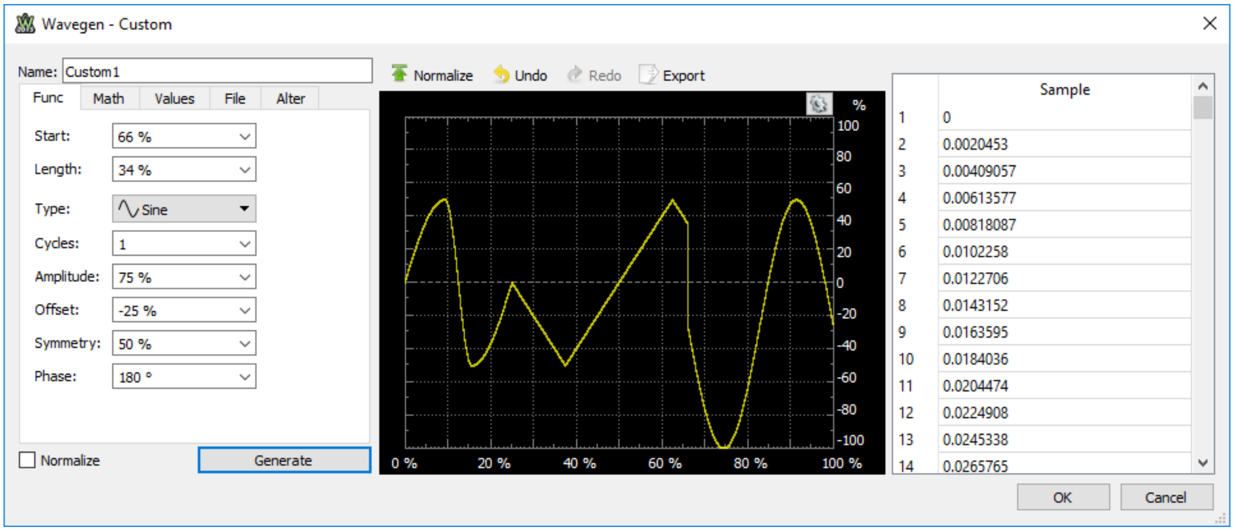
III. Results and Discussion

A. Student Products

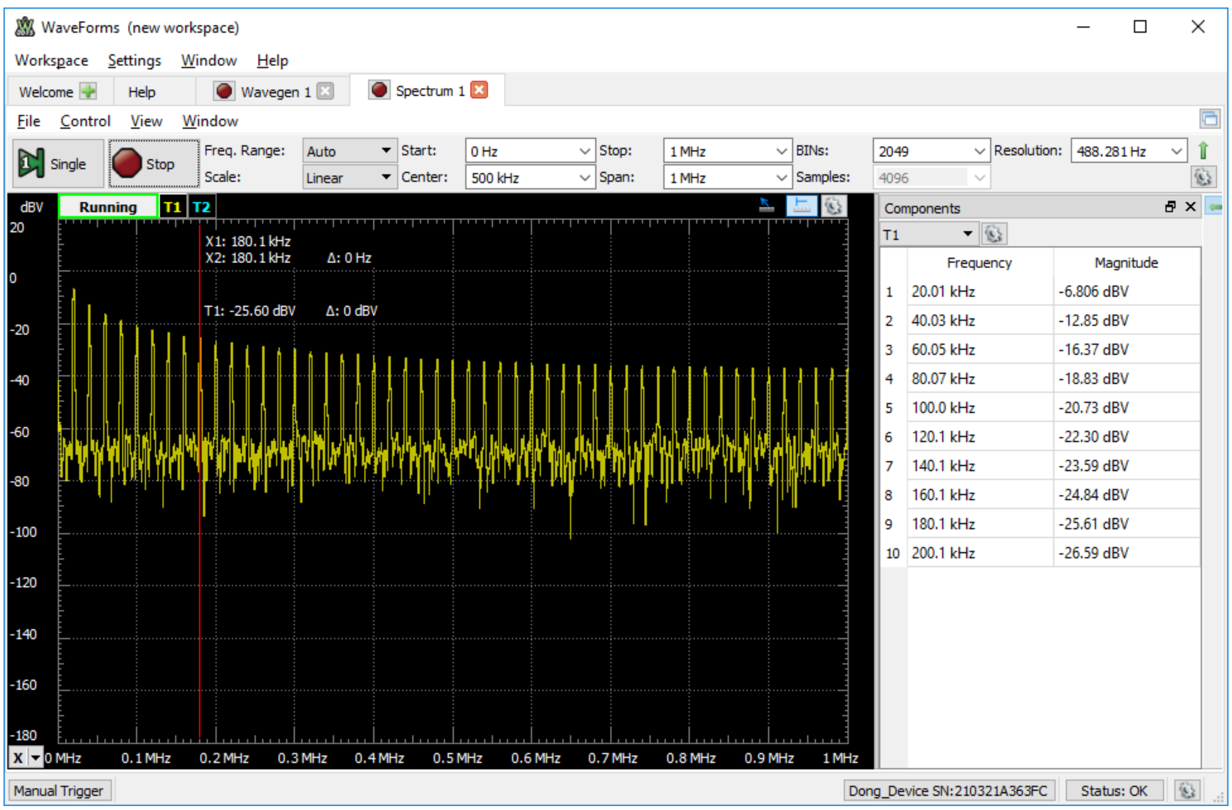
The hands-on learning experiences offered to these Fall 2017 and Fall 2018 students were varied, although the collective subject matter falls within the overarching category of 'biomedical instrumentation.' This section presents snapshots of student work related to each of the scripted learning experiences: Labs 1→5, as laid out in Table 1 and Table 2, supplemented by additional *Section II* text. Results that relate to the follow-on wearable ECG project are not included here, since the Fall 2017 project work was already presented in an ASEE 2018 paper [23], and the Fall 2018 project work is summarized in an ASEE 2019 manuscript accepted for publication [24].

A Digilent Analog Discovery 2 hardware unit and the accompanying Waveforms 2015 virtual instrumentation software were employed by each student in each of the five scripted laboratories. The figures on the following pages present highlights of the related student work:

- Figure 3 depicts screen shots from ***Lab 1 - Getting Started with the Analog Discovery 2***. These include an example screen for the waveform generator and an example screen for the spectrum analyzer. As noted in Table 1, these vetted tutorials went well for all of the students enrolled in the course, and each student was able to practice signal creation, acquisition, and analysis skills useful for the other four scripted laboratories and the follow-on project.
- Illustrative results for ***Lab 2 – Bioamplifier Fundamentals*** are presented in Figure 4 and Figure 5. Figure 4 highlights the frequency-sweep approach used to characterize the lowpass and highpass filters provided by a commercial CB Sciences ETH-255 two-channel bioamplifier [25]. Representative signals acquired with the accompanying piezoelectric transducer and ECG hardware are pictured in Figure 5.
- Figure 6, as a pictorial summary of ***Lab 3 – Active Lowpass Filters***, depicts the circuitry, transfer function, and transient response for a similar set of second-order lowpass filters built by ECE 773 students: a Sallen-Key configuration and a multiple-feedback configuration. For this work, each student is given the tasks of building each filter and then comparing the behavior of the two filters in terms of their spectral behavior and stability.
- Details related to ***Lab 4 – Biomedical Electrodes*** are illustrated in Figure 7 and Figure 8. Figure 7 depicts one student's overall PSpice circuit schematic, the transfer function for that circuit sequence, and the breadboarded version of the circuit. Electrocardiograms obtained by those circuitry and the circuitry design by a second student are portrayed in Figure 8.
- Figure 9 completes the representative set of student work by displaying a finger clip and a photoplethysgram produced for ***Lab 5 – Photoplethysmography***.

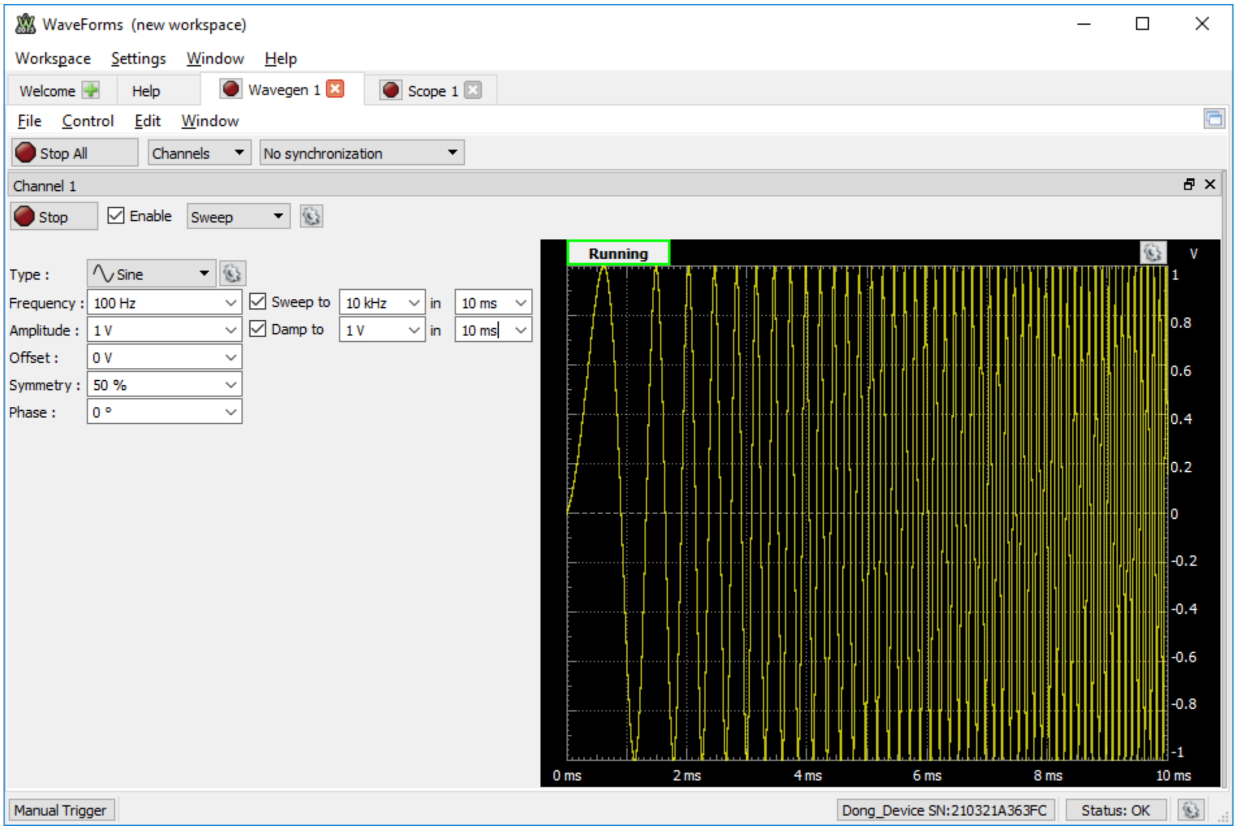


(a) Waveform generator example screen, courtesy of Student A.

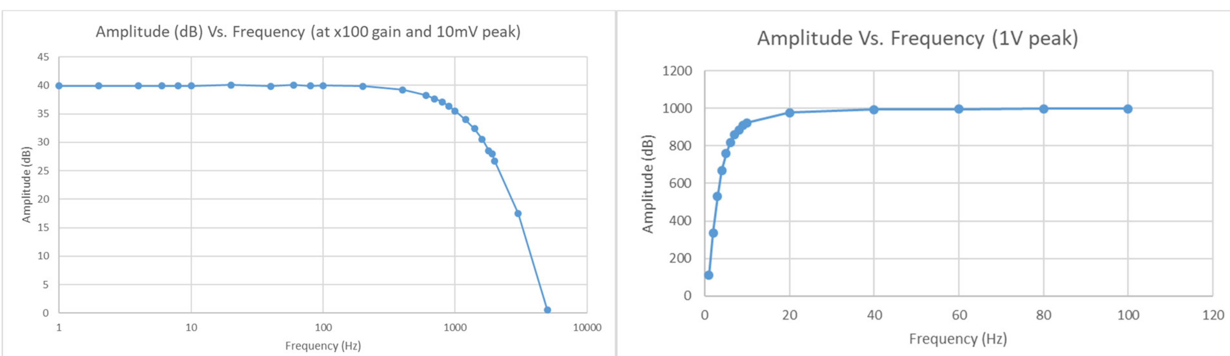


(b) Spectrum analyzer example screen, courtesy of Student B.

Figure 3. ***Lab 1 – Getting Started with the Analog Discovery 2*****: Representative Waveforms 2015 screens for (a) the waveform generator and (b) the spectrum analyzer.**

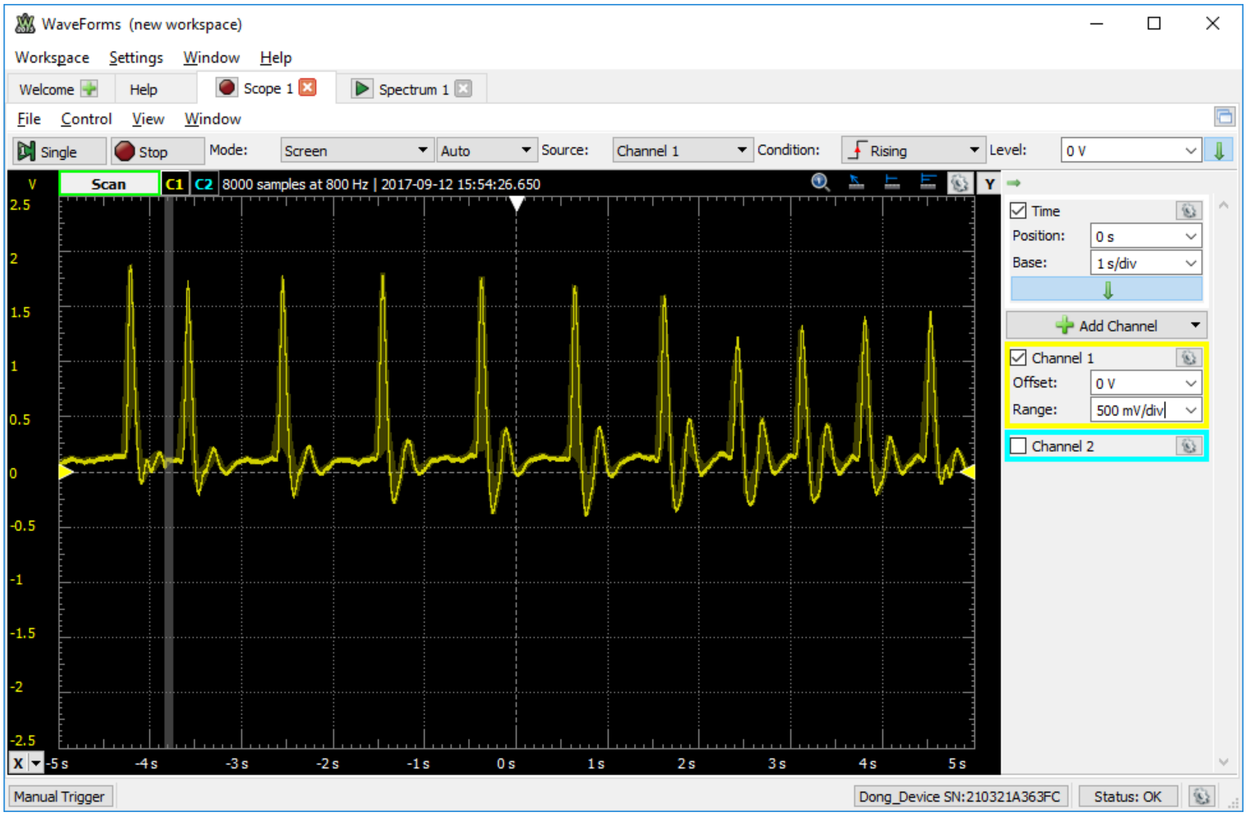


(a) AD2 sine wave frequency sweep (100 Hz to 10 kHz) used to observe the frequency response of the lowpass filter (courtesy of Student B)

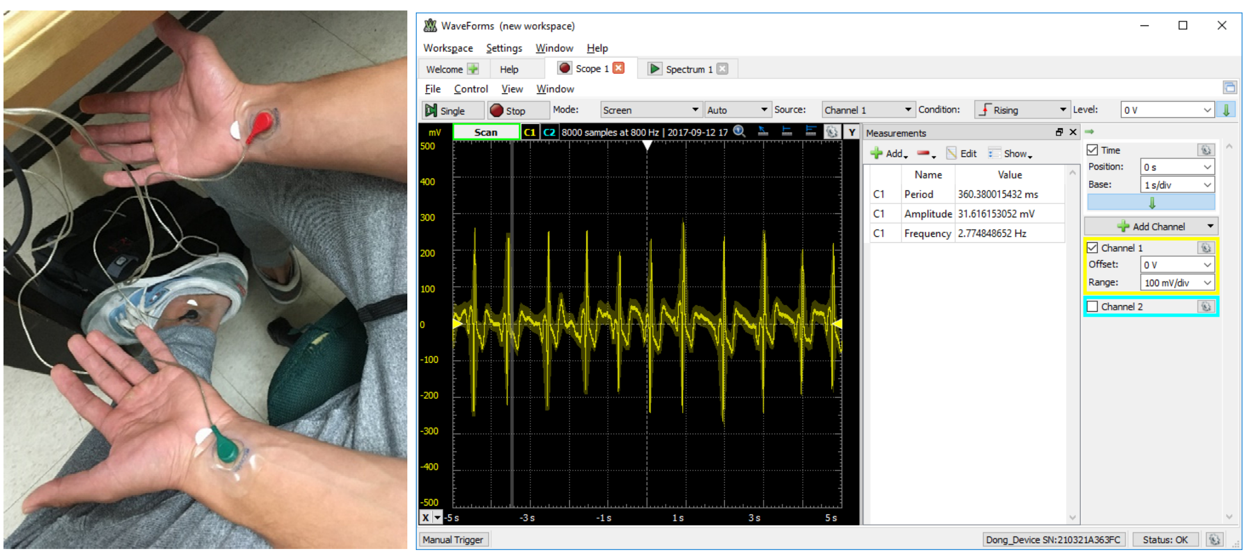


(b) Measured transfer functions for the ETH-255 lowpass (left) and highpass (right) filters. Lowpass filter: –3 dB at 800 Hz with a rolloff of ≈ 40 dB/decade (two-pole filter). Highpass: –3 dB at ≈ 4.5 Hz with a rolloff of ≈ 20 dB/decade (one-pole filter) (Courtesy of Student A)

Figure 4. *Lab 2 – Bioamplifier Fundamentals*: (a) excitation frequency sweep for the ETH-255 lowpass filter and (b) representative measurements for the ETH-255 lowpass (left) and highpass (right) filter transfer functions.

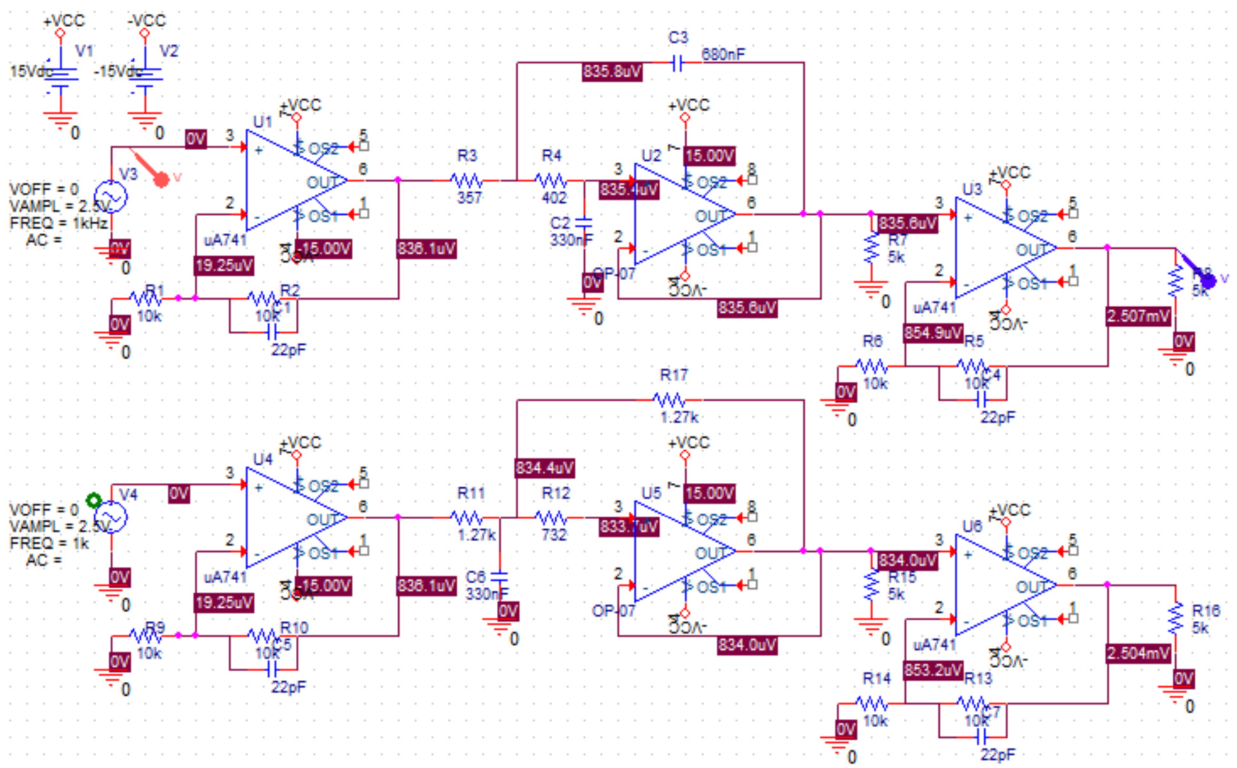


(a) Piezoelectric plethysmogram acquired from the left index finger (courtesy of Student B). The integral of this signal will visually match the shape of a traditional optical photoplethysmogram.

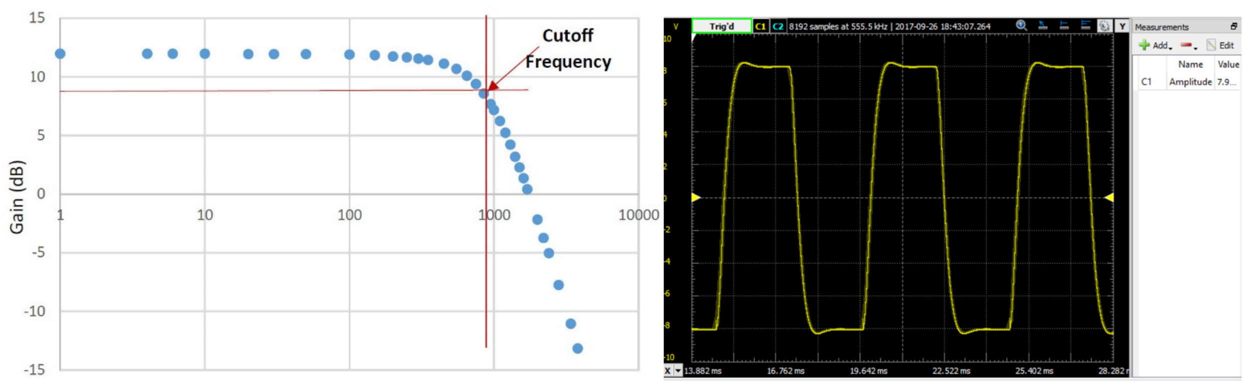


(b) Single-lead electrocardiogram obtained with a gain setting of 10, a 0.3 Hz high pass filter, and a 50 Hz lowpass filter (courtesy of Student B).

Figure 5. *Lab 2 – Bioamplifier Fundamentals*: (a) representative signal from a piezoelectric transducer wrapped around the left index finger and (b) a typical electrocardiogram acquired with a pair of wrist-worn electrodes.

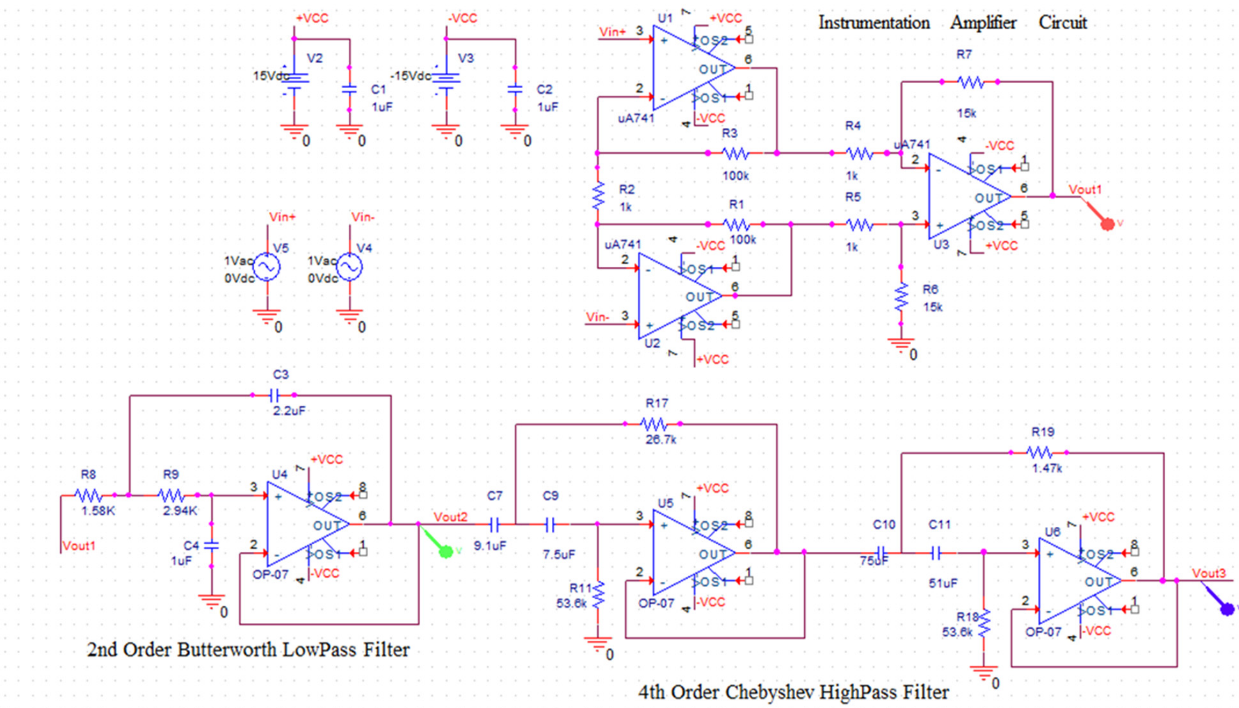


(a) Sallen-Key (upper) and multiple-feedback (lower) filter schematics, courtesy of Student C.

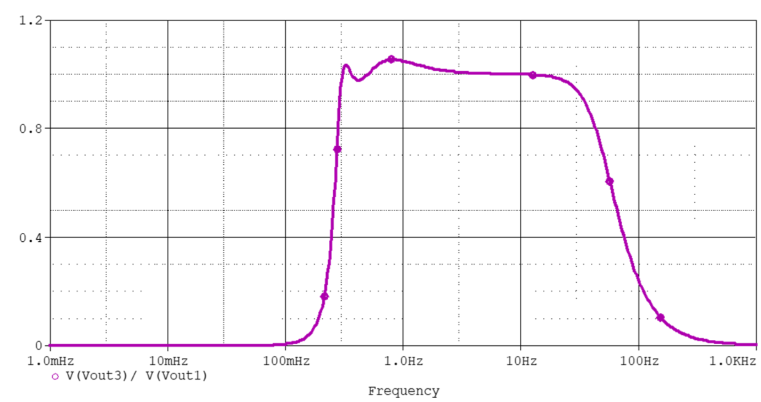


(b) Frequency response data (left) and transient response waveform (right) for a 200 Hz lowpass filter obtained with the Digilent AD2 and Waveforms 2015 toolset. (Courtesy of Student C.)

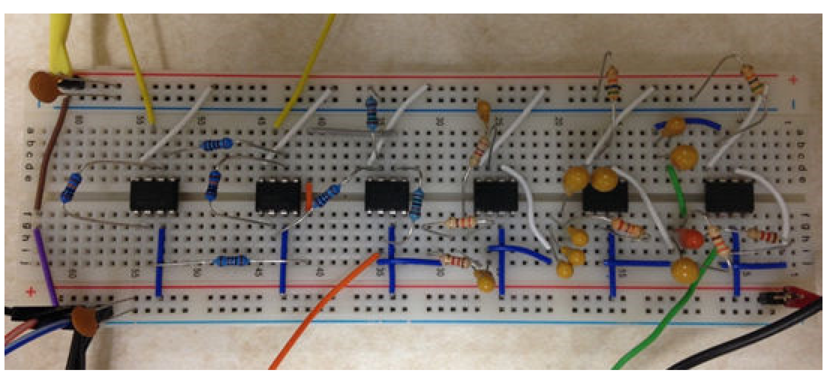
Figure 6. *Lab 3 – Active Lowpass Filters*: (a) lowpass filter schematics and (b) representative data acquired with the Digilent portable toolkit.



(a) PSpice schematic for an electrocardiograph amplifier/filter cascade, courtesy of Student A.



(b) Electrocardiograph circuit transfer function, courtesy of Student A.



(c) Breadboarded electrocardiograph circuit, courtesy of Student A.

Figure 7. ***Lab 4 – Biomedical Electrodes*****: Representative electrocardiograph circuitry.**

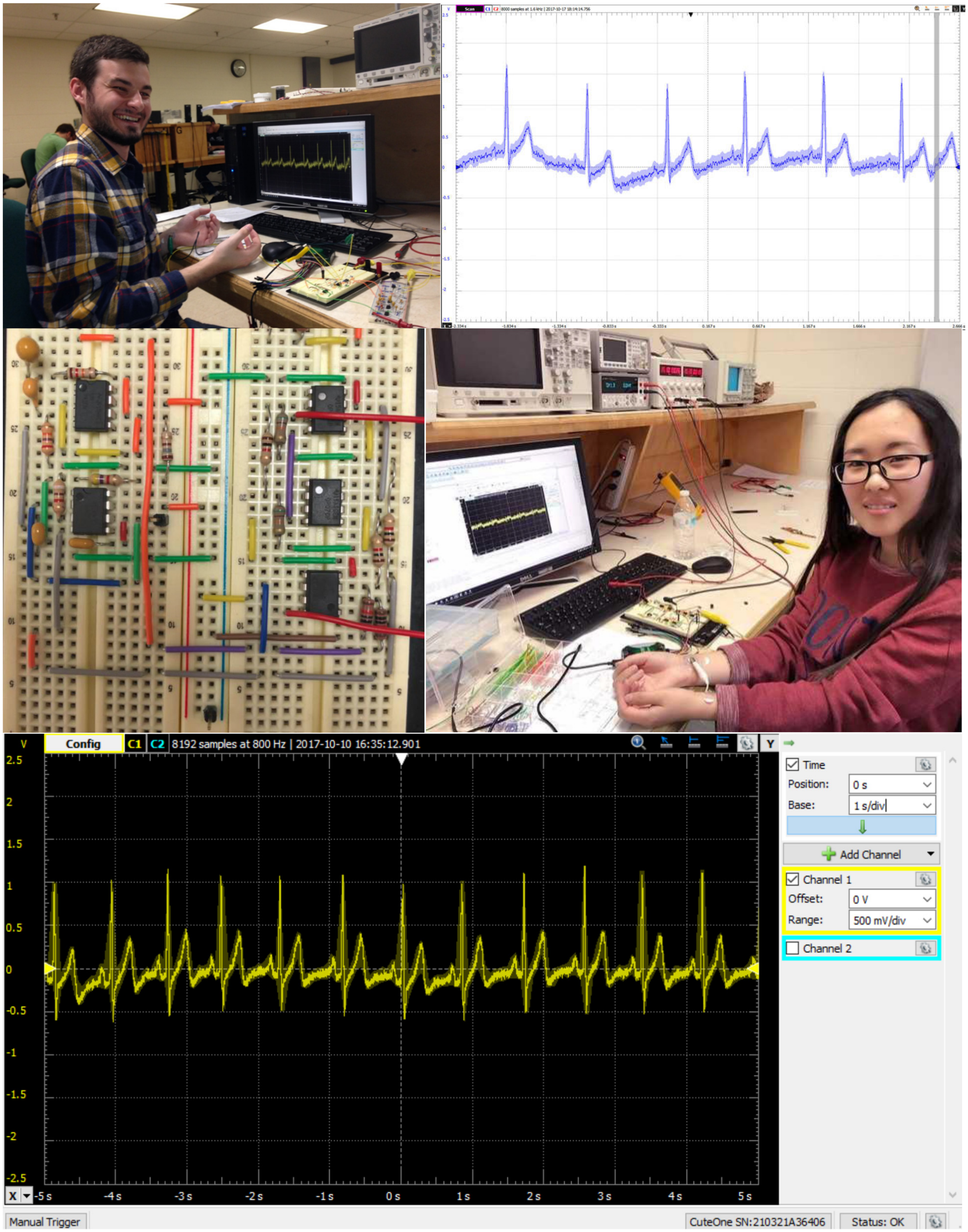


Figure 8. ***Lab 4 – Biomedical Electrodes*: Representative signals courtesy of Students A & C. All circuit excitations and signal acquisitions were managed with the Digilent toolset.**

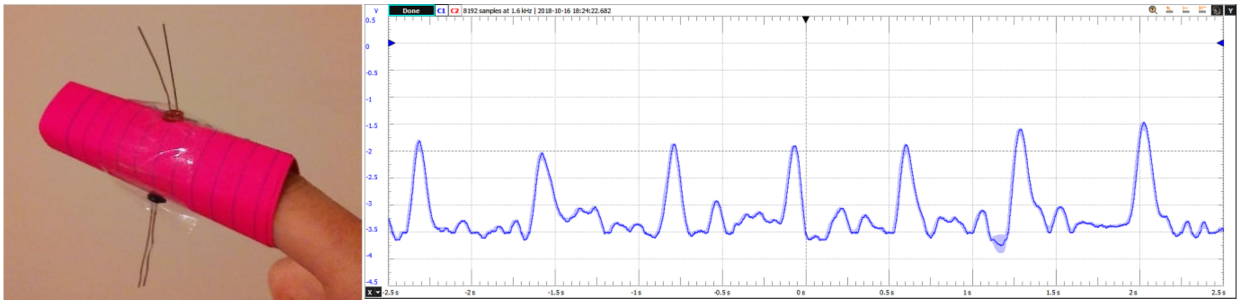


Figure 9. ***Lab 5 – Photoplethysmography*: Custom finger clip (left, courtesy of Student D) and representative photoplethysmogram (courtesy of Student E).**

B. Learning Objectives

Learning objective assessment results are presented in Table 2 in Section II. As is apparent from the table, a substantive amount of work was involved in correlating the scores on various laboratory protocols (the "Point Value" or "PV" column in Table 2) with their corresponding learning objectives. If an individual student's score (relative to a PV for a particular set of protocols) exceeded a certain value, then they were considered to "meet" that learning objective. Given that nearly all students met nearly all learning objectives, it is reasonable to infer that the AD2 and Waveforms toolset did not *detract* from learning in any way, but rather sensibly aided learning. In a number of cases, the "F18 Met" value exceeded the "F17 Met" value by 1 (or by 2 in a few cases), but it is unclear whether the difference was the result of the availability of a TA in F18 or simply the difference in student pools. In short, the learning objective results for the scripted laboratories were encouraging, especially in light of the new Digilent toolset employed by the students.

C. Survey Results

When considering the combined Fall 2017 [23] and Fall 2018 student survey data, only three students out of sixteen ranked their self-perceived understanding of "Virtual Instrumentation" above 2 out of 5 in the pre-project survey. In the post-project survey, only one student ranked their understanding lower than 4 out of 5. The aggregate *increase* in score was 2.5 ± 0.97 (mean ± stdev). Clearly, the students' self-perceived understanding of virtual instrumentation was greatly improved. Their self-perceived understanding of "Digilent Analog Discovery 2" experienced even greater improvement, yielding an aggregate score *increase* of 3.22 ± 0.91. It is interesting to note that all of the Fall 2017 students ranked their understanding of this topic at 1 out of 5 in the pre-project survey. For this topic, only two out of the eight Fall 2018 students recorded a self-perceived understanding above 2 in the pre-project survey. For the "Digilent Analog Discovery 2" topic, no student recorded a self-perceived understanding below 4 in the post-project survey data.

D. Additional Thoughts

The instructors made other situational observations about the use of the AD2 units as each semester progressed. As an initial thought, from the viewpoint of an instructor that wishes to make changes to a class, it is important to consider the idea, "first do no harm." Given the ease with which students can learn to use these Digilent tools to excite circuits, visualize signals, and log data, any worry about moving the wrong direction when attempting to help students is gone.

They can sensibly meet the learning objectives and finish their work without experiencing too much frustration caused by the new toolset. The tutorials are clearly straightforward and can be completed in a reasonable amount of time by any of the students, and online video supplements to tutorials are available and effective. The Waveforms 2015 software is easy to install and use, adding little overhead to the overall process. Further, the voltage acquisition ranges and quantization levels are suitable for this class of biomedical signals. Finally, the AD2 price point appears to be sensible to the students in lieu of a course textbook.

On the other hand, students need better instruction when using the frequency domain analysis tools in Waveforms, as the settings make a tremendous difference in terms of the sensibility of the resulting spectra. Regarding the hardware, the numerous wires coming out of the harness attached to the AD2 connector can be an issue when working with a breadboard and other nearby electrical elements. The breadboard breakout [26], available on the Digilent web site, would be a good help with regard to the breadboard and should be included in the normal AD2 distribution. Finally, the breadboard bundled in the parts kit is a bit too small for any practical work, but Digital does sell a large breadboard at a reasonable price.

Ideally, the ECE 773 instructors would have had access to two groups of students: a control group that could work through these scripted laboratories with traditional equipment, and a test group that could address the same laboratories with the AD2 and Waveforms toolset. This was impractical for several reasons: the number of students per fall offering was insufficient, TA support would have been difficult to find, and the lab experiences were updated in numerous ways mid-stream. The instructors did note that the presence of an experienced TA during Fall 2018 made a big difference in terms of both delivering the scripted laboratory content and managing the wearable ECG design project. For the Fall 2017 work, a TA was unavailable. The Fall 2018 TA had also taken the Fall 2017 version of the course.

IV. Conclusions

Portable, USB-enabled data acquisition tools offer students the ability to build and debug circuitry outside of the confines of traditional benchtop laboratory spaces. While these tools have been utilized with a growing number of lower-level, undergraduate circuits and electronics courses, they have not been widely adopted in higher-level courses that deal with more specialized material. This paper shared lessons learned from the initial utilization of Digilent Analog Discovery 2 units in a senior-level biomedical instrumentation laboratory course. Subject matter addressed portable-unit tutorials, bioamplifiers, active filters, electrode-based circuitry, and photoplethysmographs. These portable units functioned overall well as alternatives for traditional benchtop equipment in this context, as they helped students to meet learning objectives for these laboratories and provided straightforward mechanisms for circuit excitation, signal visualization, and data logging, while meeting a price point commensurate with a typical college textbook.

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