AC 2012-5114: LESSONS LEARNED FROM THE APPLICATION OF VIR-TUAL INSTRUMENTS AND PORTABLE HARDWARE TO ELECTRODE-BASED BIOMEDICAL LABORATORY EXERCISES

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Lessons Learned from the Application of Virtual Instruments and Portable Hardware to Electrode-Based Biomedical Laboratory Exercises

Abstract

Portable data acquisition hardware and virtual instruments offer students the flexibility to complete laboratory assignments at home, alleviating traffic in conventional laboratories while at the same time offering an instructional mode more consistent with the students' connected lifestyles. To that end, the authors used support from the National Science Foundation CCLI (TUES) program to develop a hardware platform referred to as a Rapid Analysis and Signal Conditioning Laboratory (RASCL) unit. This tool offers a power supply, a large-area breadboard, an analog function generator, two electrically-isolated input channels, and a collection of connectors for input/output signals. Analog and digital signals from the circuitry on this board are sent via a ribbon cable to a National Instruments (NI) myDAQ[®] personal data acquisition unit, which then connects through a USB port to a computer running the NI LabVIEW[®] software. Students therefore have access to a collection of virtual instruments coupled with the hardware necessary to build and test circuitry at home.

This paper focuses on the improved design of the version 4.0 RASCL board with respect to the usability of the electrically isolated channels and the quality of the resulting signals. The design effectiveness was assessed within the context of a Fall 2011 course: *ECE 772 – Biomedical Instrumentation*. These laboratory exercises addressed variants of electrode-based biomedical circuitry, including electrocardiographs and electrooculographs, where the use of isolated channels added a necessary safety layer. Each student worked with their own RASCL unit and built the base circuitry for these exercises around a traditional instrumentation-amplifier-based core. PSpice simulations corroborated anticipated circuit behavior. Students assessed the frequency content of each of the respective signals prior to designing and building the appropriate filter circuitry. Laboratory report assessments, coupled with end-of-semester surveys, indicated that (a) learning objectives were met, (b) student experiences were positive, and (c) the resources provided by the portable toolset were sensible alternatives to benchtop hardware that would normally be employed in those exercises.

I. Introduction

Mobile data acquisition (DAQ) toolkits offer potential in secondary engineering education to (a) reduce cost and overcrowding issues experienced in static benchtop laboratories, (b) add handson exercises to formerly lecture-only courses, and (c) offer mobile learning experiences to students who are used to immediate access to electronic support tools¹⁻⁹. Given access to such kits, students could debug circuitry at home prior to their laboratory session so that they do not spend all of their in-laboratory time getting their circuits to work, which means more time for analysis and discussion with the laboratory instructor.

Options for such tools have been limited (refer to ⁵ for a tool listing with citations), which led the authors to develop the original RASCL platform,^{2, 5-7, 9}. This platform offers a power supply, a large-area breadboard, an analog function generator, two electrically-isolated input channels, and

a collection of connectors for input/output signals. Analog and digital signals from the circuitry on this board are sent via a ribbon cable to a National Instruments (NI) myDAQ[®] personal data acquisition unit¹⁰, which then connects through a USB port to a computer running the NI LabVIEW[®] software. Students therefore have access to a collection of virtual instruments coupled with the hardware necessary to build and test circuitry at home.

This paper presents recent upgrades to the RASCL board (version 4.0) that improve function generator operation, signal quality, and the usability of the two electrical isolation input channels supported on the board. The updated design was utilized individually by students in a Fall 2011 *ECE* 772 – *Biomedical Instrumentation* course to address variants of electrode-based biomedical circuitry, including electrocardiographs and electrooculographs; applications where electrical isolation is important. Laboratory report assessments and end-of-semester surveys provided data to help determine (a) if learning objectives were met, (b) whether students found the tools to be sensible alternatives to benchtop instrumentation, and (c) if students would be willing to invest in such a resource given its potential use in many electrical and computer engineering courses.

II. Methods

A. Tool Features and Specifications

National Instruments myDAQ[®] **Platform.** The RASCL version $3.0^{5, 6}$ and 4.0 designs were partially driven by the August 2010 release of the National Instruments myDAQ[®] personal instrumentation platform (see Figure 1). The myDAQ platform (an NI USB-6009 upgrade) adds $a \pm 5/\pm 15$ V power supply (0.5W), a software-controlled function generator (frequency ≤ 100 kHz), a digital multimeter, and two audio I/O jacks. It hosts two analog inputs (16-bit, 200 kS/s), two analog outputs (16-bit, 200 kS/s), and 8 TTL/CMOS digital I/O lines. Drivers and VIs are based on the NI ELVISmx software¹¹ used with NI ELVIS II¹². Available VIs include an oscilloscope, a waveform generator, a digital multimeter, a power supply, a digital I/O interface, and a frequency-domain Bode analyzer.



Figure 1. National Instruments myDAQ® personal instrumentation platform.¹⁰

RASCL Version 4.0. Top, side, and bottom views of the RASCL version 4.0 design are depicted in Figure 2 through Figure 4. This design is a cohesive collection of the following hardware features:

- More efficient and functional layout via a multi-layer printed circuit board
- Connectors for input/output signals (5 banana jacks, 2 co-axial connectors, and 4 audio jacks)
- Two 2" by 6" breadboards, with rigid breadboard-to-computer trace connectivity
- Terminal strip that gives direct access to all RASCL connectors and myDAQ input/output channels
- Function generator: better knobs/performance (sine, triangle, & square waves; 0.01 Hz to 1 MHz)
- External power supply with earth ground access (+5 V_{dc} (3 A); +12 V_{dc} (1 A); -12 V_{dc} (0.5 A))
- Two electrically isolated input channels with improved ease of use and signal-to-noise characteristics
- Wrist strap to protect circuitry from electrostatic discharge
- Power supply switches/fuses and power-on LED indicators

The assembly can be carried inside a plastic case (see Figure 5). Figure 3 and Figure 4 illustrate that the myDAQ unit can be secured beneath the RASCL board by way of four screws. RASCL version 4.0 retains power supply and function generator capabilities from versions 2 and 3 since (a) the USB bus can only draw 500 mA, and the myDAQ needs ~250 mA to operate and (b) the myDAQ function generator can only (ideally) provide signals that contain frequencies up to 100 kHz. The entire collection (RASCL + myDAQ + Student LabVIEW license) costs ~\$325.



Figure 2. RASCL version 4.0 top view.



Figure 3. RASCL version 4.0 side view.



Figure 4. RASCL bottom view.



Figure 5. RASCL design inside a plastic carrying case.

B. Electrode-Based Learning Experiences in ECE 772 – Biomedical Instrumentation

Kansas State University (KSU) and East Carolina University (ECU) team members involved in this NSF-funded effort (see the *Acknowledgements* at the end of the paper) are developing virtual-instrument-based learning experiences for courses at KSU (*ECE 512 – Linear Systems; ECE 772 – Biomedical Instrumentation*) and ECU (*ENGR 3014 – Electric Circuits; ENGR 3050 – Instrumentation and Controls*). Early results from the ECU experiences are presented in previous FIE 2010⁷ and ASEE 2011⁹ papers. In Fall 2010, two KSU laboratory experiences were offered:

- a combined session that included a RASCL tutorial session and an active-filter exercise, and
- a session that focused on instrumentation amplifiers to acquire electrocardiograms.

These Fall 2010 KSU experiences were offered in the context of *ECE 628 – Instrumentation* as a substitute for *ECE 772* because the latter was not offered that term. A summary of these experiences can be found in an ASEE 2011 paper.¹³ In Fall 2011, these KSU sessions were repeated within the context of *ECE 772* using the updated RASCL version 4.0 design. Further, an electrooculogram (EOG) laboratory was added that utilized the base circuitry developed for the ECG laboratory. The following sections focus on the electrode-based laboratories given that the effectiveness of these learning experiences is more closely tied to the RASCL version 4.0 upgrades.

Electrocardiogram (ECG) Laboratory

ECG Laboratory – Overview. The goal of this laboratory is to introduce students to instrumentation amplifiers and their practical use in a biomedical electrode application such as electrocardiography. To this end, each student will build instrumentation-amplifier-based circuitry to acquire and filter electrocardiograms (ECGs). The design element for this laboratory will involve the configuration of a cascade of suitable filters to remove unwanted signal elements while keeping the desired signals intact. The exercise will utilize a cyber-laboratory learning kit consisting of a newly-developed Rapid Analysis and Signal Conditioning Laboratory (RASCL) board, a National Instruments (NI) myDAQ[®] USB data acquisition module, and a set of NI LabVIEW[®] virtual instruments (VIs).

ECG Laboratory – Learning Objectives. Upon completion of this laboratory, each student should be able to do the following:

- Place ECG electrodes at meaningful locations on the human body
- Construct circuitry to acquire differential signals from body-worn electrodes
- State the advantages of an instrumentation amplifier over a simple difference amplifier
- Acquire and analyze signals using the RASCL, myDAQ, and LabVIEW toolset
- Utilize the two isolation channels on a RASCL board
- Describe the features of time-domain ECGs
- Relate time-domain features of ECGs to their corresponding frequency spectra

- Design filter circuitry to remove unwanted ECG signal components while retaining desired signal components
- Archive the results of such an experience in an electronic format

ECG Laboratory – Condensed Protocol. In preparation for this laboratory, the students first configure the virtual oscilloscope as in the active filters laboratory. They then construct the electrocardiograph (ECG) depicted in Figure 6, where one of the primary learning objectives is to gain familiarity with the isolation channel hookups. They are then asked to create a follow-on filter sequence (as in Figure 7) that will remove undesirable signal components. An ECG virtual instrument (see Figure 8) is available to help them visualize their signals in the time and frequency domains. Rather than use written laboratory notebooks, students are asked to record data/images from each major element in a Microsoft Word file. The Word files are then used to provide grades and to verify that the learning objectives were met.



Figure 6. Example circuit for a medical ECG monitor.¹⁴



Figure 7. ECG filter cascade.



Figure 8. ECG acquisition and analysis VI.

Electrooculogram (EOG) Laboratory

EOG Laboratory – **Overview.** The goal of this laboratory is to introduce students to instrumentation amplifiers and their practical use as applied to electrooculography. To this end, each student will build instrumentation-amplifier-based circuitry to acquire and filter electrooculograms (EOGs). The design element for this laboratory will involve the configuration of a cascade of suitable filters to remove unwanted signal elements while keeping the desired signals intact. The exercise will utilize a cyber-laboratory learning kit consisting of a newly-developed Rapid Analysis and Signal Conditioning Laboratory (RASCL) board, a National Instruments (NI) myDAQ[®] USB data acquisition module, and a set of NI LabVIEW[®] virtual instruments (VIs).

EOG Laboratory – Learning Objectives. Upon completion of this laboratory, each student should be able to do the following:

- Place EOG electrodes at meaningful locations on the human head
- Construct circuitry to acquire differential signals from body-worn electrodes
- State the advantages of an instrumentation amplifier over a simple difference amplifier
- Acquire and analyze signals using the RASCL, myDAQ, and LabVIEW toolset
- Utilize the two isolation channels on a RASCL board
- Describe time- and frequency-domain EOG features
- Relate time-domain features of EOGs to their corresponding frequency spectra
- Design filter circuitry to remove unwanted EOG signal components while retaining desired signal components
- Archive experiences and results in electronic format

EOG Laboratory – Condensed Protocol. For the EOG laboratory, each student configures the virtual oscilloscope as in the ECG laboratory. They then verify that the ECG acquisition and filter circuitry from the prior laboratory (see Figure 6 and Figure 7) are still functional. Next, they update their acquisition circuitry consistent with the circuitry in Figure 9 to optimize its use for EOG applications. Once their circuit is operational, a student places two electrodes on their temples toward the outside of each eye; a reference electrode is placed on their forehead or cheek. They then seek to obtain an electro-oculogram based on the same principles that guide ECG acquisition. In this context, a glance to the left should generate a time-domain "pulse," and a glance to the right should generate a similar pulse but with the opposite polarity. A custom EOG VI (see **Error! Reference source not found.**) is provided to assist them with the process. As before, rather than use written laboratory notebooks, students are asked to record data/images from each major element in a Microsoft Word file.



Figure 9. Example circuit for an EOG monitor.



Figure 10. EOG acquisition and analysis VI.

C. Assessment Surveys

At the end of the semester, the authors gave the ECE 772 students the following survey in an effort to better understand their experiences with these learning tools and their impressions of the technology. Ten of the eleven students responded. Rather than list the categories again in the Results & Discussion section, the **survey results (in a bold font) are also contained on the following pages** to save space. The numbers in the far right column are the mean (\bar{x}) and standard deviation (σ) for the numerical values reported.

This semester we used portable instrumentation kits in ECE 772 that each included National Instruments (NI) LabVIEW virtual instruments, an NI myDAQ personal data acquisition unit, and a KSU-designed Rapid Analysis and Signal Conditioning Laboratory (RASCL) board. The following survey was created to gather feedback regarding this toolset and the associated learning experiences.

			erate		llent		
Overall Perceptions	² oor		Mode		Exce	x	σ
Rate your overall experience with the <u>tools</u> themselves. Rate your overall experience with the <u>topical laboratories</u> .	① ①	2 2	3 3	4) 4)	(5) (5)	3.9 3.9	0.5 0.5
Rate your ability to acquire and analyze signals with this portable toolset.	1	2	3	4	5	4.2	0.6
Note the potential impact that these types of hands-on exercises, even if simple, could have on the effectiveness of traditionally lecture-only courses like Circuit Theory I/II or Linear Systems.	1	2	3	4	\$	3.8	0.7
Note the potential impact of the ability to do hands-on circuit work <u>at home</u> versus in the Engineering complex.	1	2	3	4	5	3.9	0.9
Specify the value of recording experimental results from such experiences in electronic format instead of handwritten notebooks.	1	0	3	4	5	4.1	1.2
What level of ownership and interest would be added on your part if assembling your own RASCL unit was part of the ECE curriculum?	1	0	3	4	\$	4.0	0.8
Topical Learning Experiences	None		Some		Much	x	σ
How much learning occurred during theactive filter session?	0	2	3	4	5	3.8	0.7
electrocardiography session?	1	2	3	4	5	4.2	0.4
electrooculography session?	1	2	3	4	5	3.8	0.7
 the hands-on element? 	1	2	3	4	5	3.5	0.7
 the visual nature of the software interface? 	1	2	3	4	5	3.7	0.5
 How much instrumentation amp interest was added because of the hands-on element? 	1	2	3	4	5	3.6	0.8
 the visual nature of the software interface? 	1	2	3	4	5	3.6	0.7
 How much electrocardiography interest was added because of the hands-on element? 	1	2	3	4	5	4.0	0.9
the visual nature of the software interface?	1	2	3	4	5	3.8	1.0
How much electrooculography interest was added because ofthe hands-on element?	1	0	3	4	5	3.9	0.7
 the visual nature of the software interface? 	1	2	3	4	5	3.6	0.8
Regarding circuit construction on the breadboard	1	2	3	4	5	3.2	0.6
 what level of distraction did it add? What level of welcome diversion did it add? 	1	2	3	4	5	3.1	0.8

Topical Learning Experiences (cont.)	lone		ome		luch	x	σ
When you compare your prior <u>filter</u> familiarity with your familiarity	2		0		2		-
with filter concepts after using these portable tools, what level of							
How filters affect cinusoids at different frequencies	M	Ø	য	A	6	2 1	10
 How filters affect non-sinusoidal signals 	0	Ø	3	(† (4)	S	3.1	1.0
 Challenges that analog filters nose during construction 	0	Ø	3	@	S	3.5	0.5
Theoretical versus experimental filter transfer functions	0	0	3	(4)	5	3.6	0.8
Simulation of frequency-domain filter performance	1	2	3	(4)	(5)	3.6	1.0
Performance differences in SK versus MFB filters	1	2	3	4	(5)	3.7	1.0
When you compare your prior instrumentation amplifier familiarity						• · ·	
with your familiarity with these same concepts after using these							
portable tools, what level of understanding was added in the following areas?							
 The ability of an instrumentation amplifier to help remove 	\bigcirc	Ø	ঞ	a	S	27	06
common-mode signals	U	C	9	U	9	3.7	0.0
 The benefits that instrumentation amplifiers offer over simple difference amplifiers 	1	2	3	4	\$	3.9	0.7
 The need to follow an instrumentation amplifier with a 	ſ	Ø	3	4	S	35	0.8
cascade of suitable filters	U	•	٢	U	٢	5.5	0.0
When you compare your prior <u>biomedical electrode</u> familiarity with							
your familiarity with this same concept after using these portable							
tools, what level of understanding was added in the following							
dreds:	M	0	(3)		ß	20	1 1
Placement locations for biomedical electrodes	0	Ø	9 0	•	6	5.0 1 1	1.1
Circuitry to acquire signals from biomedical electrodes	\bigcirc	Ċ	9	9	0	4.1	1.2
 Types of signals one can acquire with biomedical electrodes 	1	2	3	4	5	4.0	1.1
 Time-domain shapes of signals provided by biomedical electrodes 	1	2	3	4	5	3.6	0.8
 Frequency content of signals provided by biomedical electrodes 	1	2	3	4	5	3.5	0.8
 Relationships between the time-domain components and their corresponding frequency-domain spectra 	1	2	3	4	5	3.5	0.8
 Time- and frequency-domain differences between ECG and 	\bigcirc	(2)	3	(4)	(5)	3.8	1.0
EOG signals.	0	0	0	0	0	0.0	
Filters appropriate for ECG and EOG signals.	0	2	(3)	(4)	(5)	3.4	0.9
Specific Tool Functionality							
	Sult		tral		>		
How easy to use was/were the	ij		len		as	v	~
BASCI prototyping area?		\bigcirc	Z 3	4	Ш S	л 41	07
 BASCI power supply? 	0	0	3	(4)	G	4.5	0.7
BASCL guick connect terminal block?	0	2	3	(4)	(5)	4.3	0.5
RASCL function generator?	0	2	3	4	5	4.0	0.8
RASCL electrical isolation channels?	1	2	3	4	5	3.3	1.2
• myDAQ analog I/O channels?	1	2	3	4	5	4.0	0.4
• Standard LabVIEW VIs for the myDAQ unit?	1	2	3	4	5	3.9	0.7
ECG and EOG VIs?	1	2	3	4	(5)	3.9	1.1

Written Responses

How much time do you estimate was required for each of the portable labs?

Active Filters: <u>5.8</u> hours; ECG: <u>5.7</u> hours; EOG: <u>4.5</u> hours

Would you prefer to learn instrumentation concepts using handwritten assignments, hands-on assignments, or both?

Handwritten: 0; Hands-On: 4; Both: 6

With the exception of ECE 210/502/628, have you ever built circuits and tested the theoretical concepts learned in lecture-format classes?

Yes: 5; No: 5

What improvements/features might be added to the RASCL/myDAQ system to improve its ...

Usability?

- Use better capacitors to reduce the noise in the isolation channels.
- I think the RASCL/myDAQ system is very useful and I can't think of any ways it could be improved on at the moment.
- The isolation channels were a bit confusing at first. The frequency and magnitude knobs for the function generator are a bit too small.
- We might expand the size of the RASCL board so that we may easily build circuits without consideration of space and make the circuits look more effective.
- Improve isolation channel performance & power supply hookups.
- It is sometimes difficult to match terminal block holes to labels.
- Adding a print screen button may be a good idea.
- Make it easier to adjust frequency.

Durabiilty?

- Put protection or glue around the board to protect it.
- Better encasement. The box is too small to fit all of the wires and components. I also feel like the external power cord connector is going to break off one of the times when I pull on it.
- A case for the integrated circuits on the board, plus more structural support near the middle.
- A carrying case with more room for breadboard circuitry (the top often crushed my wiring).

• The board has good durability.

Capability?

- The isolation channel still needs to be cleaned up but is far better than the previous ones.
- Improve the isolation design.
- Add one more +-5V power supply.

What is the most you would pay for a system like this if it were used in several classes over the course of your academic career?

____\$0 ___\$50 ___\$100 ___\$200 ___\$300 ___\$400 ___\$500 (check one) Average response: ~\$205

How would you prefer to pay that amount? ___lump sum ___payments across semesters LS: 4; PAS: 7

Would you prefer to pay a lesser amount as 'lab fees' each semester to fund the purchase and upkeep of a set of RASCL units that would be available for check out? ____Yes ____No

Yes: 6; No: 5

Do you have any other thoughts that you would like to add?

- I really like how the RASCL boards were incorporated into the labs. I thought they were very useful.
- Overall, using the RASCLs was a pleasant experience. However, if the kits are truly meant to be portable, it may be nice to provide a kit of commonly used chips/resistors/caps so labs could be done at home (may be distributed in the beginning of the semester for a class using the boards)
- If possible, a bigger carrying case with room for wiring kits would be handy.

III. Results and Discussion

A. Learning Objectives

The learning objectives for the electrode-based laboratories were subjectively assessed through personal observations as well as the Word files that the students submitted as laboratory reports. Although a written exam or lab practicum experience would have helped to quantify sub-levels of learning relative to these objectives, most of the objectives were met by default because every student was able to build circuitry to successfully acquire and filter these signals. Objectives such as "State the advantages of an instrumentation amplifier ..." or "Describe the features of time-domain ECGs" would have been better assessed in a post-laboratory quiz; this is a lesson learned for the next offering of the ECE 772 course in Fall 2012. One shared learning objective that was not clearly met was the objective stated as "Relate time-domain features of ECGs/EOGs to their corresponding frequency spectra." This is not a subject that was addressed in the lecture portion of this course, partially because a reasonable understanding of frequency-domain analysis is required to verbalize a response. Some of these students had not taken a linear systems course prior to the end of the Fall 2011 semester; it is not a prerequisite for ECE 772.

Given the subjective nature of the learning objective assessments, the authors wish to focus more attention on the results of the student surveys. These yield interesting insights regarding student impressions of these technologies, as discussed in the next section.

B. Student Surveys

An ordered summary of the survey responses is a sensible way to address these results. First, it is important to note that themes bear more value than the survey numbers themselves, as data only exist for 10 students. From the *Overall Perceptions* section, the overall response to these tools was encouraging but on average lower than expected: most of the response averages hover around a score of 4.0, which indicates the students were content but not thrilled. On a positive note, these responses are markedly higher than responses to similar surveys given at the end of the Fall 2010 section of ECE 628.¹³ Those responses ranged from 3.0 to 3.9 on average, with an outlier of 4.3 that relates to the potential of these tools rather than the students' actual experiences. At first glance, it seems reasonable to attribute these higher scores to improvements

made in these RASCL tools, particularly with regard to the function generator, the isolation channels, and the board labeling.

The students do indicate that the tools could be useful to acquire and analyze signals as an addon to typically lecture-only courses. That positive thought is tempered by the lackluster responses to the questions about the potential of these tools to support experiences at home. Given the recent improvements to the tools, the authors assumed that student enthusiasm to use these tools in their own environments would increase. On the contrary, not all of these students have the necessary minimal computing resources at home to support these tools. Further, ready access to (a) electronic components (e.g., through research laboratories, the parts shop, or the laboratory support staff), (b) corroborating benchtop laboratory equipment (e.g., oscilloscopes, multimeter, and spectrum analyzers), and (c) other students is a disincentive to leave the confines of the engineering environment and work at home. Therefore, to realistically gauge the effectiveness of this teaching approach, the instructors may need to mandate at-home work during the next offering of this course.

Regarding the *Topical Learning Experiences*, the self-reported learning that occurred was moderate across the board for all topical categories. This is encouraging. Approximately one third of these students were graduate students, and the rest were EE undergraduate students that were reasonably far along in their curriculum. While they did not report much learning in areas such as filters and transfer functions (which they have seen in various forms in different courses), topics related to electrodes did map to learning (e.g., placement locations, electrode circuitry, time-domain signal shapes, and differences in ECG versus EOG signals).

Feedback on the actual tools was the highlight of the survey results. The students responded positively to that thought that building such a toolkit (at least populating the board) would be a good ownership exercise as part of the curriculum. Ease-of-use responses were high for the primary elements of the RASCL board, with the notable exception of the two electrically isolated channels, even though version 4.0 upgrades made the RASCL boards easier to use in this regard.

From the responses to the open-ended questions, the laboratories appeared to require an appropriate amount of student time overall (~5-6 hours per session, which usually spanned two weeks) and that the students enjoyed the hands-on emphasis. The authors were surprised that half of the students had not built and tested circuitry outside of the three classes that were noted on the survey sheet; this is an area for curricular improvement. Students did have good suggestions for board improvements, including updates to the function generator, improvements to the isolation channels (for signal quality and ease of use), and more effective case designs for the tool collection. On average, these students were willing to invest \$205 in such a resource.

IV. Conclusions

Portable data acquisition toolkits offer the potential to alleviate laboratory crowding, supplement lecture courses with hands-on exercises, and optimize the ways students use their time. This paper presented the use of such a toolkit (a National Instruments myDAQ unit coupled with a custom Rapid Analysis and Signal Conditioning Laboratory (RASCL) board) that allows students to work on biomedical circuit designs outside of the confines of the laboratory. This paper specifically addressed electrode-based topics and an assessment of those experiences from the students' perspectives. Assessment surveys indicate that students find the toolset to be a sensible alternative to benchtop instrumentation and that they would be willing to invest in such a resource, which offers potential for use in myriad EE courses.

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