Converting a Biomedical Instrumentation Lab From In-person to Online

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***Abstract*—Many laboratories were converted to an online format to support students unable to attend instructional laboratories in person during the COVID-19 pandemic. During conversion of a biomedical instrumentation laboratory at a large public research university, our goal was to maintain the lab learning objectives and as much interaction with physical circuits and equipment as possible for students participating either at home or in the traditional on-campus laboratory space. This innovative practice work-in-progress paper describes the process used to convert each laboratory experiment and observations of instructional staff throughout the spring 2021 semester.**

Keywords—undergraduate, biomedical engineering, remote laboratory

I. Introduction

During the COVID-19 pandemic, many laboratories were modified to meet the needs of in-person, online, or hybrid instruction formats. One of these labs was a biomedical instrumentation laboratory at a large public university in the Midwest. The pre-pandemic version of the lab had seven planned experiments and a project. For the spring 2021 semester, we also offered an entirely online version of the laboratory that could be completed by students who were not able to make it to campus for an in-person laboratory.

This paper documents the conversion of the laboratory from using expensive benchtop equipment (e.g., function generator, oscilloscope) to a low-cost version that could be shipped to students at home. The learning objectives of the lab remained basically the same. Minor changes were made to the objectives to accommodate the new equipment and software used, such as the ADALM1000 from Analog Devices, which provided function generator and oscilloscope capabilities [1].

In this paper, the process for converting and testing each of the labs will be described. The final lab kit includes some borrowed equipment and student-purchased parts. The ADALM1000 and a handheld multimeter were borrowed from the department for the duration of the course. The equipment was shipped to each student in the online section and students were responsible for returning it to campus at the end of the semester. The students were also required to purchase a breadboard, resistors, capacitors, operational amplifiers (op-amps), and a few other components.

II. Background

Instructional laboratories are a common experience for all undergraduate students majoring in engineering because laboratory experiences help link theory to practice [2]. Prior to the pandemic, traditional on-campus laboratories required engineering departments to address challenges such as such as budget constraints, space limitations, class size, and limited teaching resources [3]–[6]. During the pandemic, additional safety considerations needed to be addressed, including social distancing, reduced capacity in campus spaces, and students being unable to attend a lab in person [7]–[9].

Engineering departments offered online courses before the pandemic and had also started to provide laboratory experiences for off-campus students [10]–[12]. Laboratory kits, an alternative to traditional on-campus laboratories, can solve many of the challenges listed above. Kits cost less than traditional laboratories and allow students to take home laboratory equipment to complete experiments on their own time [13]–[16]. Because kits are portable, they can also be shipped to students in online courses [17]. While a laboratory kit is a viable alternative to traditional laboratories, the students should still be able to achieve the intended learning objectives [16]. This paper draws upon the experiences of kits before the pandemic and early experiences in the pandemic to convert a biomedical instrumentation lab into an experience that could be done in a traditional lab space on campus or at home.

III. Method

To implement changes to a laboratory, the instructional staff must first understand the course context and objectives, then select appropriate equipment, and finally update the laboratory procedures and assignments to implement and assess student achievement of the objectives.

A. Course Context

The Biomedical Instrumentation Laboratory (BIOE415) course is required for all Bioengineering students at a large public university in the Midwest. It is cross listed as an Electrical and Computer Engineering elective. Prior credit or concurrent enrollment in the Biomedical Instrumentation (BIOE414) is also required. The lab course is split into two meetings each week. On Mondays, students from all sections meet at the same time for an introduction lecture. They later meet in the lab space in smaller sections throughout the week to complete experiments or work on the lab project. The laboratory objectives related to the experiments include:

1. Analyze, design, and construct operational amplifier and instrumentation amplifier circuits to amplify biosignals.

2. Analyze, design, and construct filter circuits to filter unwanted signals from biosignals.
3. Acquire electrical and biological signals by implementing virtual instruments with Agilent VEE, LabVIEW, or amplifiers coupled to a computer with other software.
4. Understand biosensor and electrode design and apply them for signal acquisition.
5. Understand the limitations of instrumentation in terms of accuracy, resolution, precision, and reliability.
6. Understand the origin of cardiac and muscle biosignals and acquire data using ECG electrodes.

There are 12 complete lab stations in the lab space. Each station has a function generator, oscilloscope, DC power supply, digital multimeter, a DAQ, and a desktop computer with Windows 10 and necessary software installed. A faculty member is assigned to every section and conducts the Monday introduction lectures. A graduate teaching assistant and undergraduate assistants help the students complete the laboratory experiments. The faculty member is available during each lab section and periodically checks in on the progress of experiments.

Several adjustments were made to the lab during the pandemic. The introduction section moved online. The enrollment cap was reduced to ten students for each lab section and a second undergraduate assistant was added to support each lab section. All the students enrolled in the course worked alone at their own lab bench or at home. The online students received support via Zoom or Campuswire (a platform with chatrooms, and question/answer features). Additionally, learning objective three was temporarily modified since the change in hardware also required a change in software.

B. Equipment Selection Process

There were several factors that were considered during the equipment selection for the online version of the lab. The first consideration was that students might complete the lab at home and interact with the instructional staff online, or they might do so in person in the existing lab space. As in-person and online students would share the same introduction section, the same portable equipment was used for all to provide consistency.

The next factor was budget and logistics. The oscilloscope, function generator, power supply, and multimeter needed to be replaced with lower cost and easy to ship components. A simple handheld digital multimeter was selected, as well as the ADALM1000 to replace the function generator and oscilloscope, and 9V batteries to replace the power supply. The total cost of this equipment was around $55. The ADALM1000 and multimeter were shipped to each online student at the start of the semester. Each student signed an agreement that they would return the equipment at the end of the semester or be charged for replacing it. All students needed to purchase a breadboard, resistors, capacitors, op-amps, jumper wires, and temperature sensors. The whole kit (borrowed plus purchased) was about $120 before shipping costs.

C. Lab Procedure Development

After the equipment was selected, the next step was to update each lab experiment. This turned out to be the most challenging step in the process. As the ADALM1000 is powered by USB, the function generator and oscilloscope functions are limited to a range of about 0-5V. Gains, offsets, and filters needed to be modified in most of the experiments. To finalize these changes and ensure the overall experiment would work, the updating process started by building the complete circuit and testing it with the new equipment and updated values. Then once the final circuit worked, each step of the original laboratory procedures was updated to match the new circuit.

IV. Preliminary Results

All the laboratory experiments were successfully converted to work with the new equipment, however, more significant modifications were required than anticipated. There were also several lessons learned along the way that should be carefully considered for future labs.

A. Conversion of Experiments

The first lab is an introduction to the equipment, so it had the most change to the procedures. The limitations of the equipment did not limit the scope of the procedures. In practice, shipping delays for parts and software installation caused unexpected problems. For the students completing the lab in-person, the university was able to provide the few resistors and bread board needed to complete the lab, however, that was not an option for the students in the online section. So, some students fell behind in the first lab. The other issue that arose for some of the online students was installing the software to interface with the equipment and updating the firmware on the ADALM1000. While neither of these were an issue with the equipment in the lab space, the variety of computers and operating systems used by online students created unexpected errors. Fortunately posts on the Analog Devices forum helped correct the firmware issues.

The second lab is an introduction to analog to digital signals and the software used on the computer to capture and analyze digital signals. The change in hardware necessitated moving from LabVIEW to MATLAB. Previously, the experiment consisted mainly of completing National Instruments' LabView training. Instead, students completed the MATLAB Signal Processing Onramp from the MathWorks. The students applied lessons learned in this training to data they collected in the first experiment. This turned out to be the smoothest experiment of the semester and allowed some of the students who fell behind in the first lab to catch up.

The limitations of the equipment and software became more of an issue in the next four laboratory experiments. In the third experiment, students built and tested op-amp circuits. Instead of using a DC power supply, the op-amps were powered by two 9V batteries. The non-inverting op-amp circuit had a reduced gain to fit within the 0-5V range. The inverting op-amp was a bit more challenging to adjust to fit into the 0-5V range. For this circuit, the students did two separate tests. The first test grounded the non-inverting input as it would be in a traditional inverting configuration and the students measured the output with the DMM. To see how a time-varying signal is amplified with the circuit, two different outputs of the ADALM1000 were used: the non-inverting input was connected to the 2.5V source and the output of analog channel A was set to be a sinusoid that varied between 2.5 and 3.0V. The one part of the experiment that could not be completed with the ADALM1000 was identifying the bandwidth of the op-amp. Since understanding the limitations of bandwidth and measuring the gain-bandwidth-product are an important component of the experiment, the staff recorded data with the function generator and oscilloscope in the laboratory and provided the data to the students to analyze as part of their post-laboratory reports.

In the fourth experiment, students built and tested a passive RC low pass filter and an active high pass filter. For the low pass filter the ADALM1000 was used as a source for the sinusoidal inputs with a DC offset and then measured the output on the second channel. The same modifications were made to the active high pass filter as the inverting op-amp in the previous experiment. Then the high pass and low pass circuits are combined to create a bandpass filter. The last part of this experiment is to test digital filters and analyze the power spectrum of a signal. In the past, this signal was passed through the bandpass filter created in the previous step and read into the computer using a NI DAQ, then a digital bandstop filter was applied using LabVIEW. Given the limitations of the ADALM1000 for capturing data, this part was adapted to be completed entirely in Simulink.

In the fifth experiment, students built and tested an instrumentation amplifier and input protection circuitry. This circuit also had the same adaptations as previous experiments. The built-in REF pin on the instrumentation amplifier was useful in creating an offset in the output. This experiment also included measuring the bandwidth of the instrumentation amplifier, so the data was collected in the lab and provided to students as in previous experiments.

The sixth experiment combines the circuits in experiments four and five to create an electrocardiograph (ECG). This turned out to be the trickiest experiment to convert. Ultimately, the high pass component of the bandpass filter was removed so that the DC offset added by the instrumentation amplifier would not be removed. This kept the output between 0 and 5V. However, that did not solve all issues: For some subjects the leads on the arms needed to be reversed to keep the signal positive, which caused the ECG signal to appear inverted. This circuit is the hardest circuit for students to wire and debug in the original lab and the modifications and limitations of the ADALM1000 added extra complications for debugging.

In the last experiment, the students compared two different temperature circuits: silicone bandgap and thermistor. They were able to measure the steady-state output voltage for both sensors with the DMM. Slight modifications to the circuits were made so the ADALM100 could also be used to see how the voltage changed over time. The last step was to measure the time constant of each sensor when a cold pack or hot pack is applied to the circuit. Another limitation of the ADALM1000 is that it can only save the last 10 seconds of data, but the time constant for both sensors is greater than that. As with other experiments, staff collected this data in the lab and provided the data to students.

B. Additional Considerations

These seven experiments were successfully converted, and all students were able to complete each lab either in-person or online. However, there were other logistical challenges during each section that changed the way students completed the lab and added unexpected challenges. The PixelPulse software recommended by Analog Devices to interface with the ADALM1000 was buggy and difficult to use. Therefore, we planned to switch to MATLAB's data acquisition toolbox to interface with the ADALM1000. However, these features do not work in MATLAB Online or MATLAB for macOS. Since there were students in the online section that only had access to computers with macOS, this feature could not be used as planned. Helping students debug circuits was another challenge because many students enrolled in the course have limited or no experience wiring breadboards. It seemed like the in-person sections went about as smoothly as the fall semester when students also worked alone and had received most of their debugging support from staff. The students in the in-person sections spent about the same amount of time on the labs as students in the fall semester labs. However, the online students seemed to take longer as it was much more difficult for course staff to assist with debugging over Zoom and chat, with only static cell phone pictures to view the circuit and identify issues. The online section also had twice as many students as any of the in-person sections.

C. Student Feedback

Eleven of the 59 enrolled students completed end-of-semester evaluations. They rated the overall quality of the course at 3.73 on a 5-point scale. Open-ended comments suggested eliminating the online version going forward because of the frustrations of debugging over Zoom. There were multiple comments about improving the clarity and organization of laboratory experiment instructions. One student suggested that a lab partner would be beneficial. Also, one student stated, "Some minor blips in the labs but that's to be expected." Based on this feedback and instructor observations, it seems that the new version of the lab met their expectations for a new laboratory experience delivered with the limitations of the COVID-19 pandemic.

V. Conclusion and Future Work

Overall, the semester went as well as could be expected for a new set of labs with new equipment. Students in all the sections completed all seven experiments and therefore achieved the corresponding learning objectives. There are improvements that could be made in the future to support peer-to-peer debugging and clarifying some of the steps in the experiments. However, the limitations of the equipment and the difficulties with the PixelPulse software cannot be addressed unless there are updates from Analog Devices. Future work in this project will be to analyze laboratory practical exam scores and student reflections to quantify achievements of the learning objectives and identify other changes to the lab based on student experiences.

ACKNOWLEDGEMENT

The author would like to thank all the instructional staff of this course for their support throughout the spring 2021 semester.

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