

2006-971: DIGITAL SIGNAL PROCESSING AND BIOINSTRUMENTATION USING LABVIEW, THE NEW ELVIS BENCHTOP PLATFORM, AND BIOPAC

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Digital Signal Processing and Bioinstrumentation using LabVIEW, the new ELVIS Benchtop Platform, and BIOPAC

Abstract

Students interested in biomedical instrumentation and the signal processing of biomedical signals are sometimes at a disadvantage compared to a traditional electrical engineering student. They often have not had as many courses or as rigorous a treatment of many of the foundational topics important to instrumentation and signal processing. To help rectify this situation, we created a two-course bioengineering sequence that makes extensive use of LabVIEW and ELVIS from National Instruments and various BIOPAC products. This paper includes a description of the courses, the associated lab exercises, student responses, and recommendations.

1 Introduction

A new, two-course sequence in biomedically-oriented digital signal processing and bioinstrumentation has been created by the Electrical and Computer Engineering Department at the University of Wyoming. While bioengineering students have shown a high degree of interest in these topics, their background and preparation in traditional signal processing and instrumentation is often not as strong as a traditional electrical engineering student. For example, electrical engineering students take courses in circuit theory, electronics, linear systems, and digital signal processing, all of which apply in some way to bioinstrumentation and biosignal processing. Furthermore, most bioinstrumentation and biosignal processing textbooks assume prior knowledge of these areas.¹⁻⁷ Yet there are many students who wish to learn more about bioinstrumentation and biosignal processing who either have not taken all these foundational courses or do not feel well prepared in these areas. To meet this pedagogical challenge, the authors have incorporated a large number of demonstrations and laboratory exercises into these courses, based upon our experience that this greatly aids learning.⁸⁻¹² We take advantage of a new and highly flexible tool for educators: the new ELVIS benchtop platform combined with the latest version of LabVIEW, both now available from National Instruments (www.ni.com). In addition, the authors integrated various BIOPAC products (available from BIOPAC Systems, Inc., www.biopac.com) with ELVIS in a way not seen before. The results of using this approach have been highly successful.

ELVIS stands for Educational Laboratory Virtual Instrumentation Suite. It provides an integrated benchtop platform for prototyping, design, testing, measurement, and data analysis with multi-instrument functionality. When coupled with LabVIEW software, a standard data acquisition card,

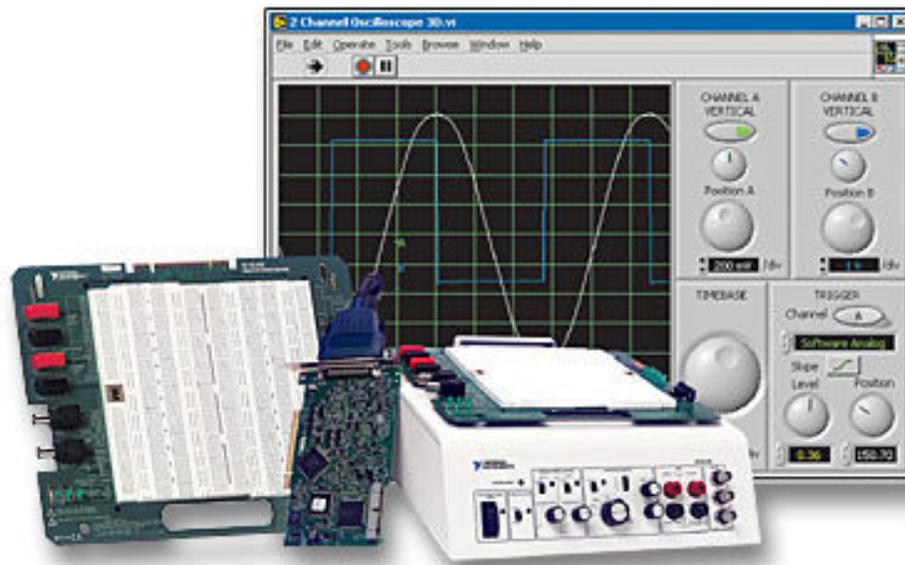


Figure 1: The ELVIS benchtop platform, with an expanded view of the prototyping board, a data acquisition board, and an example of one of the included software virtual test instruments (the 2-channel oscilloscope) user interface. Figure courtesy of National Instruments, Inc.

and either a desktop or laptop computer, a complete suite of virtual instruments (oscilloscope, digital multimeter, function generator, power supply, bode plot analyzer, etc.), is available along with a large, easily interchangeable prototyping area. The interchangeability of the prototyping board allows specialized third-party or university-developed boards to be used with ELVIS. Using this tool greatly reduces the overall cost of the required lab equipment while helping the educator to reinforce theory through practical hands-on learning. The ELVIS system is depicted in Figure 1.

For biomedically-oriented courses, the BIOPAC products have also proven quite useful. We have a laboratory populated with BIOPAC Model MP35 amplifier/interface units, and have found them quite easy to use. Specialized electrodes and sensors (such as for electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, electrooculogram, plethysmograph, etc.) are also available from BIOPAC and, when combined with the preconfigured amplifiers and interfaces, allow easy and seamless acquisition of these biomedical signals. BIOPAC also supplies software modules to make the use of their products very straightforward. However, in a course sequence such as the one described in this paper, our primary pedagogical goal to teach students the *underlying theory* and *recommended practice* of correctly interfacing such signals from a human to a computer, along with the subsequent digital signal processing of those signals. For this purpose, the standard BIOPAC approach proves to be far too seamless, providing a “black box” solution. That is, the standard BIOPAC setup hides nearly all the instrumentation and signal conditioning details from the students. We therefore developed innovative ways to interface the specialized elec-

trodes directly to ELVIS so that students are required to confront the instrumentation challenges that BIOPAC normally hides from them. From this approach, they can learn about when differential inputs are needed, how to electrically isolate the patient, and other important topics. These points would have been obscured by the standard BIOPAC devices.

This paper will describe the course content, the computer-based laboratory exercises developed, and the specifics of how LabVIEW, ELVIS, and BIOPAC products were combined to reinforce the desired topics. Lessons learned, student feedback, and overall results of using this approach will be included.

2 A Two-Course Sequence

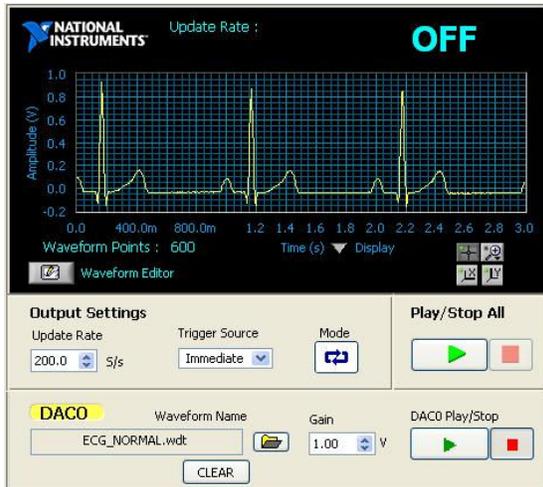
To meet the needs of our bioengineering and other interested students, we created two courses: BE4810 *Bioinstrumentation*, and BE4820 *Biodata Systems*. The courses were purposely designed such that a student could take the courses in any order, or take just one of the two courses. Both courses were conducted in a combined lecture/laboratory room, and included a series of integrated laboratory exercises. For both courses, the subsystems on ELVIS were either controlled via software or were set manually from the protoboard/workstation. Every lab exercise used LabVIEW, and some exercises (particularly pre-labs for BE 4820) used MATLAB. Since the lab portion of these courses is the primary pedagogical improvement, we will focus most of the following discussion on the lab exercises.

2.1 *Bioinstrumentation*

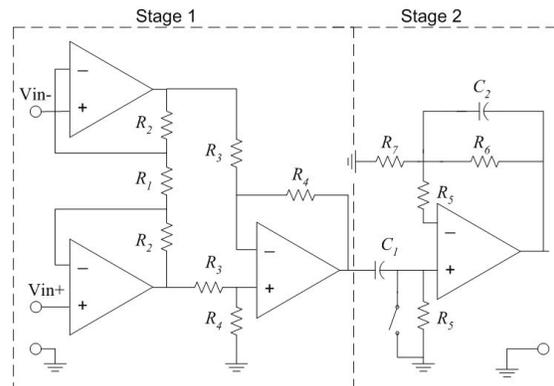
The Bioinstrumentation course was designed to introduce the student to the challenges of how to safely and accurately acquire biomedical signals from a human patient. Lecture topics included transducers; transducer interface design; ideal and non-ideal operational amplifiers; instrumentation amplifiers; biopotentials and biopotential electrodes; various signals such as EMG, ECG, and EEG; and electrical safety. The primary course text was Webster.¹ Each student was required to independently research a specific bioinstrumentation topic, write a 10-page paper describing the topic, and present it to the class.

There were five laboratory exercises specifically designed for this class, which are listed below. Note: Nearly every lab exercise used at least one of the ELVIS built-in power supplies (± 15 V and 5 V). Also, some labs used a stand-alone Agilent oscilloscope and function generator, to give the students some experience with traditional test equipment.

- Lab 1: Operational Amplifiers and Applications
 - ELVIS: Digital multimeter, function generator, variable power supply, analog input channels, built in LEDs.
- Lab 2: ECG (Electrocardiogram) Analysis and Acquisition



(a) Artificially generating an ECG signal with the Arbitrary Waveform Generator and ELVIS.



(b) A differential interface circuit built on the ELVIS prototype board for the ECG electrodes.

Figure 2: Two aspects of Lab 2 for the the Bioinstrumentation course.

- ELVIS: Arbitrary waveform generator, 9-pin DSUB (i.e., D-9 subminiature) connector for BIOPAC electrodes lead set, analog input/output channels, oscilloscope.
- Lab 3: EMG (Electromyogram) Analysis
 - BIOPAC MP35 data acquisition system: Electrodes to channel 3, communicates with LabVIEW via USB. LabVIEW then displays EMG with use of preset filters and A/D conversion of BIOPAC MP35 data.
 - ELVIS: arbitrary waveform generator (generates EMG signal from BIOPAC), analog output channels.
- Lab 4: Pulse Oximetry
 - Datex Ohmeda earlobe or finger clip probe.
 - ELVIS: Analog input channels, analog output/counter output channels.
- Lab 5 - LabVIEW and the Electro-Oculogram (EOG)
 - ELVIS: 9-pin DSUB connector for BIOPAC electrodes lead set, analog input channels, DMM (configured in LabVIEW by students).

Note that in Lab 2 and Lab 5 we required students to interface electrode sets directly to ELVIS that would normally be connected to the BIOPAC MP35 amplifier/interface box. Since using the MP35 essentially “hides” important topics such as isolation, gain, and filtering, the use of ELVIS forced students to confront and assimilate these ideas in a step-by-step manner. In Lab 2, for example, students first artificially generate an ECG signal, as shown in Figure 2(a), to become familiar with the waveshape. Then, they have to build a differential interface circuit for the ECG electrodes on the ELVIS prototype board, as shown in Figure 2(b). They use this circuit to obtain actual ECG signals from their lab partner.

2.2 Biodata Systems

The Biodata Systems course assumed that the biomedical signals have already been acquired, and concentrates on how to process these signals for various purposes. Lecture topics included an introduction to biomedical signals; analog to digital conversion; concurrent, coupled, and correlated processes; filtering for removal of artifacts; event detection; waveshape and waveform complexity; frequency-domain characterization; modeling biomedical systems; analysis of nonstationary signals. The primary course text was Rangayyan.⁴ In this course, just like the bioinstrumentation course, each student was required to independently research a specific biodata systems topic, write a 10-page paper describing the topic, and present it to the class.

There were five laboratory exercises specifically designed for this class, which are listed below. Note: The prelabs usually involve MATLAB. The student's MATLAB solution is then verified with LabVIEW. The Laboratory #4 prelab requires the students to create their own difference equations in LabVIEW, which are then used later during the lab. Also, some lab exercises used the Agilent function generator and oscilloscope (with built in FFT) in conjunction with the ELVIS virtual oscilloscope and dynamic signal analyzer (DSA). This allowed insightful comparison and analysis of multiple signals.

- Lab 1: Sampling and Quantization Concepts
 - ELVIS: Dynamic signal analyzer, oscilloscope, analog input channels.
- Lab 2: Finite Impulse Response (FIR) Filters
 - ELVIS: Dynamic signal analyzer, analog output channels, analog input channels.
- Lab 3: Infinite Impulse Response (IIR) Filters
 - ELVIS: Dynamic signal analyzer, analog output channels, analog input channels.
- Lab 4: Event Detection of Biomedical Signals
 - ELVIS: Dynamic signal analyzer, analog output channels.
 - LabVIEW (no ELVIS): Correlation/frequency estimation of EEG, and event detection of ECG (QRS complex).
- Lab 5: Fourier (Frequency Domain) Analysis
 - ELVIS: Dynamic signal analyzer, analog output channels.
 - MATLAB: The Phonocardiogram (PCG) Power Spectral Density. This MATLAB example reinforces frequency estimation using both a normal and a murmur heart sound.

One advantage of the lab exercises in the Biodata Systems course is that students gain familiarity with both MATLAB and LabVIEW, two of the most widely used engineering software tools in

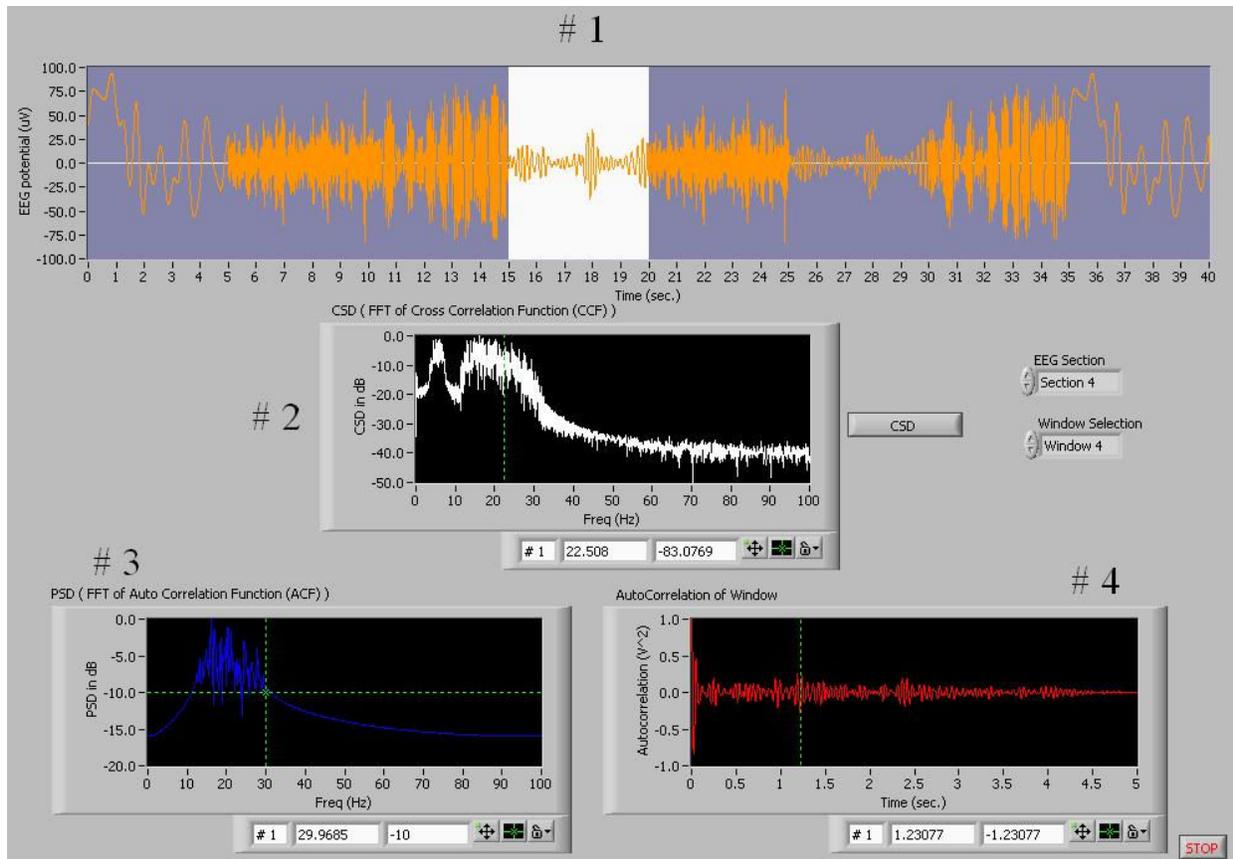


Figure 3: The user interface of a LabVIEW program (called a “VI”), written for the Biodata Systems Lab 4 exercise, which the students use to help classify EEG waveforms using the concepts of correlation and autocorrelation.

industry. Note that starting with LabVIEW version 8, most standard MATLAB code can be run inside LabVIEW if desired, even if MATLAB is not installed on that computer.

The Biodata Systems course, with the integrated laboratory exercises, provides insight into biomedically-related digital signal processing topics that is often missing in many students. An example is Lab 4, which concentrates on event detection of biomedical waveforms. Figure 3 shows the user interface of a LabVIEW program (called a “VI”) written for this lab exercise which the students use to help classify EEG waveforms using the concepts of correlation and autocorrelation. Figure 4 shows the graphical code of a LabVIEW VI written for this lab exercise which the students use to help detect the QRS complex in an ECG waveform using difference equations they designed as part of the pre-lab.

3 Advantages of Using ELVIS and BIOPAC

Using the National Instruments ELVIS provided many advantages to this two-course sequence. The virtual instrument software modules and the hardware of ELVIS provided a capability that was functionally equivalent to having a complete bank of individual test instruments and a prototyping

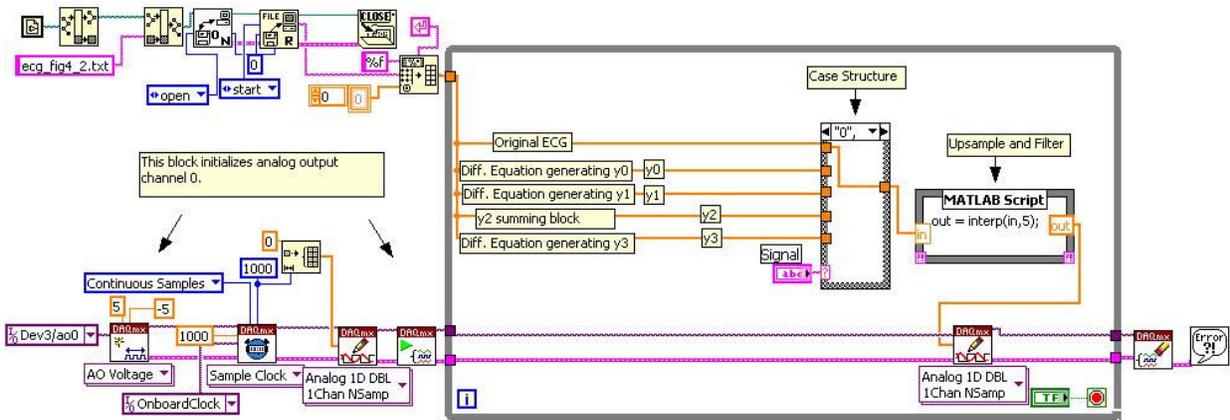


Figure 4: The graphical code of a LabVIEW VI written for the Biodata Systems Lab 4 exercise which the students use to help detect the QRS complex in an ECG waveform using difference equations they designed as part of the pre-lab.

board, and also provided superior acquisition of signals by the host PC. Virtual test instruments, a concept long championed by National Instruments, is becoming more widely accepted both for ease of use and for the lower cost it brings. Students are becoming increasingly used to video screen controls even for dedicated test equipment (as in the latest offerings from Agilent and Tektronix), so many of the arguments that have been made in the past against virtual test instruments (including those by one of the authors) are fading quickly.

The BIOPAC products are also quite useful for a bioengineering course. If desired, they can provide a seamless approach to acquiring a wide array of biomedical signals. We used the BIOPAC MP35 amplifier/interface in only a few instances, choosing to require students to take the specialized BIOPAC electrode sets and create the hardware interface themselves on the ELVIS prototype board. We found that this helped the students learn much more about biomedical instrumentation.

Combined, the two courses provide students with an interactive learning experience that also increases their familiarity with the practical uses of LabVIEW and MATLAB, exposes them to the idea of virtual instruments, and helps reinforce concepts in biomedical instrumentation and biomedical digital signal processing.

4 Lessons Learned and Student Feedback

Our own observations and the overall response from the students taking these courses has been quite enthusiastic.

4.1 Lessons Learned

As with all our courses, we maintain an “instructor’s notebook” in which we record our observations and ideas for improvement of a course as the semester progresses. A summary of our lessons

learned to date for both courses is shown below.

- **Positives:** The students really enjoyed using the BIOPAC electrode lead sets to measure and process various biomedical signals (e.g., ECG, EMG, EOG) in conjunction with the ELVIS equipment. They measured their own biomedical signals and constructed the hardware to view the signal, which appeared to amaze most of them. The students also enjoyed the pulse oximeter design in Lab #4. It helped them understand how to build for themselves a rudimentary system which is actually used every day in hospitals. The lab exercises seemed to instill in the students an even greater interest in the biomedical engineering field. ELVIS also provided easier access to power supplies, a digital multi-meter, oscilloscope, etc., since all the equipment is combined into one convenient workstation.
- **Negatives:** A lack of LabVIEW familiarity seemed to be the biggest problem. Most of the other classes offered by the ECE Department use MATLAB, so there are currently few opportunities for students to gain prior experience with LabVIEW programming. The only other negative observed to date is that many students wanted additional lab time to measure an even wider variety of biomedical signals, which would come at the cost of less lecture time.

Based upon the observations above, we intend to investigate the practicality of adding more preliminary instruction of how to use the LabVIEW graphical programming language. This would help the students better understand what the various LabVIEW VI modules are doing, and help them to create their own VIs when needed (as they do in the Biodata Systems course). We will also reassess the balance between lecture time and lab time before the next offering of these courses. Experience has shown that only about half the students take both courses due mainly to their schedule constraints, so we want to retain the “stand alone” nature of each course.

4.2 Student Feedback

At the end of the semester, we administered an anonymous questionnaire to obtain feedback from students, in particular about their attitudes regarding the lab exercises (since the lecture portion of both courses is rather traditional). This questionnaire is in addition to the standard anonymous course evaluation given for all ECE courses.

Below, we provide some of the questions from the questionnaire and a few selected responses that apply particularly to the lab portion of the courses. Note that all the student comments were positive; there were no negative responses obtained.

- *Do you feel the labs have reinforced class material in a good, bad, or indifferent way?*

Sample Responses:

- Excellent. The lab portion of this class has greatly enhanced the overall class information.

- In a good way, nice practical approach.
- The labs were great, they showed us how the instruments actually work.
- These labs really set the pace for class (Making class a much better experience).
- *Has the lab manual been straight forward and easy to understand? Do you have any suggestions?*

Sample Responses:

- The lab manual is a great piece of work and is straight forward.
- Very straight forward.
- *Did the NI ELVIS workstation, software, and LabVIEW aid in the understanding of the lab exercises?*

Sample Responses:

- The equipment was great.
- LabVIEW was very easy to use.
- Yes, the NI ELVIS and LabVIEW were very helpful.
- Yes, they did. The first lab was probably the most difficult because you had to learn how to use the equipment.
- *What other aspects do you feel would have been useful in a [Bioinstrumentation, Biodata Systems] lab?*

Sample Responses:

- Behind the scenes of LabVIEW.
- Few more bio-electronic devices (as just a demonstration).
- If there was more time, build or add onto the LabVIEW module.
- Something more bio-like. For instance an animal eye, etc.
- *[Measuring, Analyzing] various biomedical signals was a major focus for these particular lab exercises. Do you feel the labs covered appropriate [Bioinstrumentation, Biodata Systems] material?*

Sample Responses:

- Yes, in a fairly systematic way.
- Definitely, made this class worthwhile.
- Yes, in the allotted time I thought the labs covered all appropriate material.

- **ADDITIONAL COMMENTS:**

Sample Responses:

- Labs created were exactly right for this class. Don't change them!

- These were some of the best labs I have ever done.

As can be seen from the responses above, the students enjoyed the lab portion of the courses immensely. Their responses to the lecture portion of the courses were also positive overall, but more mixed as expected.

Our own observations and the written exam results confirmed that in the midst of all this “fun” the students were having, they were also learning a great deal about bioinstrumentation and biomedical digital signal processing.

5 Conclusions and Recommendations

Incorporating many demonstrations and interactive lab experiences into these two new courses proved to be very effective. While the theoretical preparation of many of the students did not include a rigorous treatment of many of the foundational topics important to instrumentation and signal processing, the practical, “hands-on” approach kept the students interested and resulted in them learning the desired topics.

By using the new ELVIS benchtop platform, combined with the latest version of LabVIEW, we were able to provide a highly integrated, easy-to-use learning laboratory environment for our students at a fraction of the cost compared to using stand-alone test equipment. In addition, the use of certain BIOPAC products with ELVIS was more educational than if we had just used the “black box” solution of the BIOPAC amplifier/interface.

The authors have advocated the use of hand-on demonstrations and interactive lab experiences in a variety of engineering courses for many years. The results of the two new courses described in this paper confirm again the validity of this approach. However, the new ELVIS product, coupled with LabVIEW, makes such an approach even easier, more affordable, and more flexible for educators. We highly recommend investigating the use of ELVIS for other courses.

The lab manuals and solutions described in this paper are freely available for educational, non-profit use, and we invite user suggestions for improvement. Interested parties are invited to contact the authors via e-mail.

Acknowledgments

The authors would like to thank the National Instruments (NI) Corporation for their support of this project. In particular, Ravi Marawar, Ph.D., Academic Program Manager at NI, was most helpful in making this project a reality.

References

- [1] J. G. Webster, ed., *Medical Instrumentation: Application and Design*. John Wiley & Sons, 3rd ed., 1998.
- [2] L. Cromwell, F. J. Weibell, and E. A. Pfeiffer, *Biomedical Instrumentation and Measurements*. Prentice Hall, 2nd ed., 1980.
- [3] R. S. Mackay, *Bio-Medical Telemetry*. IEEE Press, 2nd ed., 1993.
- [4] R. M. Rangayyan, *Biomedical Signal Analysis: A Case-Study Approach*. John Wiley & Sons, 2001.
- [5] E. N. Bruce, *Biomedical Signal Processing and Signal Modeling*. John Wiley & Sons, 2001.
- [6] R. B. Northrop, *Signals and Systems Analysis in Biomedical Engineering*. CRC Press, 2003.
- [7] G. D. Baura, *System Theory and Practical Applications of Biomedical Signals*. John Wiley & Sons, 2002.
- [8] C. J. McCormack, A. S. Ali, R. L. Haupt, and C. H. G. Wright, "Computer supplements to engineering labs," *ASEE Comput. Educ. J.*, vol. III, pp. 58–62, Apr. 1993.
- [9] S. F. Barrett, D. J. Pack, C. H. G. Wright, S. A. Stefanov, P. C. Neal, and A. R. Klayton, "Innovative student-centered educational tools for the computer engineering curriculum," in *Proceedings of the 1998 ASEE Annual Conference*, June 1998. Paper 1620-01.
- [10] T. B. Welch, B. Jenkins, and C. H. G. Wright, "Computer interfaces for teaching the Nintendo generation," in *Proceedings of the 1999 ASEE Annual Conference*, June 1999. Paper 3532-02.
- [11] C. H. G. Wright and T. B. Welch, "Teaching real-world DSP using MATLAB," *ASEE Comput. Educ. J.*, vol. IX, pp. 1–5, Jan–Mar 1999.
- [12] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "Teaching DSP: Bridging the gap from theory to real-time hardware," *ASEE Comput. Educ. J.*, vol. XIII, pp. 14–26, July 2003.