

## **AC 2007-1170: A PROJECT-DRIVEN APPROACH TO BIOMEDICAL SIGNALS AND SYSTEMS**

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## A Project-Driven Approach to Biomedical Signals and Systems

### Abstract

Signals and Systems classes often require students to apply advanced mathematics that may appear to students to be unrelated to engineering design. To bridge this gap, semester-long student driven design projects were recently implemented in a junior-level Biomedical Signals and Systems course. These projects were part of a two-phase course model and required student-led design and implementation of an automated control system to study a physiologic relevant fluid-flow phenomena.

In the first phase of the course, students progressed through a sequence of seven vertical labs that built technical and troubleshooting skills needed for their semester project. In the first lab, students recorded a pressure drop between two points in a recirculation loop composed of analog devices. The tubing between these two points was clamped and the flow rate was manually adjusted to return the pressure drop. In labs two through five, the analog pumps, flow and pressure meters, and tube clamps were systematically replaced by digital devices under the control of LabVIEW. In lab six, a stand-alone PID controller was explored qualitatively. In lab seven, the first lab was repeated with digital devices and a PID controller. Each lab was either preceded or followed by lectures on the relevant signals and systems theory and a discussion on effective troubleshooting.

In the second phase of the course, the system constructed in phase one was modified by the students to simulate a physiologic function, problem or therapy. Students were encouraged to incorporate new devices into their system and apply theoretical concepts from lecture to the design of their own system. For example, one group designed a system to simulate how peripheral blood vessels respond to hypothermia, requiring integration of a thermocouple. Progress was monitored through regular meetings with the instructor and short and focused written assignments. A 20-minute presentation/demonstrations and two-page IEEE formatted document were used to assess project management and results.

Although the example above was for a recirculating flow loop, we believe the concept of vertical labs leading toward a semester-long project is an effective way for students to learn and apply concepts taught in a traditional signals and system courses. Based upon end-of-course evaluations, we conclude that student were able to effectively translate course work to design, and develop intuition in troubleshooting.

### **Introduction and Motivation**

Biomedical signals and systems courses often focus on topics such as control systems, Fourier and Laplace transforms and signal flow diagrams. While these topics may be taught from a mathematical perspective, it is their practical application in designing and analyzing systems that are of value to the engineer. In the authors' personal experiences, signals and systems courses taught solely from the perspective of math lose the vital connections that students should make between theory and application.

In the spring of 2006, we offered a junior-level project-based course in Biomedical Signals and Systems (BMEG 350). The course integrated a number of novel teaching techniques that have been implemented in other courses and presented elsewhere as theoretical concepts. This paper illustrates how these techniques may be combined to enhance the effectiveness of a specific course. The general approach is to engage students in a number of progressive hands-on activities that strengthen their ability to apply course material to novel situations. A more practical purpose for this paper is to outline an alternative approach toward teaching signals and systems courses. Furthermore, we expect that specific aspects of this course may be applied without adoption of the entire sequence.

This paper first introduces the teaching techniques used, followed by the BMEG 350 course objectives and outcomes. The body of the paper provides details on the specific sequence of assignments leading to the semester project. Lastly, student assessment of the sequence is provided for the Spring 2006 offering, followed by instructor observations.

### **Overview of Teaching and Learning Definitions**

Our program has developed two novel teaching techniques designed to increase student participation in classes and stimulate open-ended problem solving skills through hands-on design experiences. *Vertical Labs* are a progressive sequence of hands-on experiences that introduce students to the skills and thought processes that reinforce lecture material. They are progressive in the sense that they build either to a final lab or to a novel semester-long design project. *Integrated Lecture and Lab* is a course structure that breaks down the traditional division between lab and lecture times. A typical week will consist of two hours on Monday, two hours on Wednesday and one hour on Friday. The two-hour blocks can be used for any combination of lecture or lab.

### **BMEG 350 Objectives and Outcomes**

The content, objectives and outcomes of BMEG 350 were characteristic of many signals and systems courses.

#### Global Objectives

- Think in terms of systems and signals, not individual components
- Design and build a complex system to answer a question or fix a problem
- Record, analyze and interpret the results from a system

These learning objectives were written on the board the first day of the course. They were used to motivate a discussion of the topics listed in the syllabus and justify the purpose of the semester-long design project.

### Specific Outcomes

- Apply the Laplace transform to solve differential equations
- Apply and interpret the Fourier transform of a signal
- Apply and interpret time series analysis (e.g. auto and cross correlations) of real data
- Create, analyze and reduce block and signal-flow diagrams (feedforward and feedback)
- Control a device in a system via computer
- Choose appropriate amplification, digitization and filtering routines
- Apply the concept of PID controllers
- Troubleshoot a complex system
- Relate system concepts in the wider world (economy, history, physics, sociology).

The novel aspect of BMEG 350 was the means of achieving the outcomes. The course was taught in the integrated lecture/lab format and incorporated a vertical lab sequence leading to an open-ended semester-long design project.

### **Vertical Lab Sequence**

The overall sequence of labs in the first half of the course were designed to build skills and thought processes that would be used in the semester-long design project. Groups of two or three students were self-selected and required to stay together throughout the vertical lab sequence and semester project. Throughout the descriptions below, references are made to generic lab equipment. The specific equipment used in the labs is listed in the appendix.

#### Lab 1: The Analog Recirculating Flow Loop

In previous courses (ENGR 100, BMEG 210), students constructed a manually controlled (analog) recirculating flow loop to explore relationships between terms in Bernoulli's Equation (e.g. pressures, friction, potential and kinetic energy). The first lab was designed to reacquaint student with the pumps, rotameters, and pressure gauges. Corresponding lectures focused on creating and reducing block diagrams and the concepts of feedforward and feedback.

Briefly, the lab protocol required the following steps:

- Measure the pressure drop ( $\Delta P$ ) between two points in the system (A and B) for a flow rate of 500mL/min
- Constrict the tubing (using a variable clamp) between point A and B to increase  $\Delta P$ .
- Change something in the system (not the clamp) to return the original  $\Delta P$ . Most students discover that decreasing the flow rate produces the desired reponse.
- Explain in detail the algorithm they used to find the right flow rate.
- How many adjustments did it take to get the right flow rate?
- Repeat the above to create a plot of constriction level versus flow rate.
- Draw a block diagram of the system, identifying all components and signals

Approximately 3 hours of lab time is suggested.

### Lab 2: Introduction to LabVIEW: Inputs and Outputs

The second lab was designed to confront two separate issues. First, students must have some motivation to automate their system. For example, it can be pointed out that there are real systems (e.g. blood vessels in the body, cars) that sense pressures and flows and adjust parameters accordingly. It could also be pointed out that the algorithm proposed in the previous lab would be very difficult (or impossible) for a human to carry out if the constriction was changing rapidly over time. This is an important hurdle to jump over in the course. Second, students must have some introduction to automated data acquisition (DAQ). In BMEG 350, this was accomplished using LabVIEW using the following protocol:

- Complete the 3-hour LabVIEW tutorial (available online at <http://www.ni.com>).
- Input a 0.5Vpp 10Hz sine wave from a function generator into the DAQ card and display the signal on the LabVIEW frontpanel.
- Multiply the above sine wave by two (i.e. 1Vpp 10Hz sine wave) and send the waveform out to the DAQ card.
- Display the 1Vpp 10Hz sine wave on an oscilloscope for instructor verification.

Two primary skill sets were learned in this lab. The first was the general operation and flow of LabVIEW programming. The second was a reminder of oscilloscope and function generator use as well as effective electrical wiring. These skills are necessary to complete future labs and form the basis for effective troubleshooting during the semester-long project.

For this assignment, student's received a LabVIEW VI with all of the required sub-VIs without wire connections. This models our approach in other labs, where equipment is placed on a lab bench unconnected.

Approximately 5 hours of lab time is suggested.

### Lab 3: Digital Measurements: Pressure and Flow Recordings

The third lab was designed to aid groups in acquiring and calibrating signals from recording devices embedded in their systems. Groups were challenged to:

- Power two pressure transducers and one flow meter.
- Design an experiment to calibrate the pressure transducers (relate known pressures to voltage)
- Design an experiment to calibrate the flow meter (relate known flow rate to voltage)
- Create a LabVIEW VI to:
  - Record voltages from two pressures transducers and convert to pressures.
  - Record voltage from a flow meter and convert to flow rate.
  - Display all three signals simultaneously on the LabVIEW frontpanel.
  - Save pressures and flow rate to a file on a laptop for later analysis.

- Display a live readout of estimated friction between the two pressure transducers. Here Bernoulli's Equation (discussed in a previous course) must be used to, taking into account pressure drop, flow rate, tubing diameter and any height differences.
- Optional: Include a toggle switch on the file output. On each toggle the file name will automatically be incremented.

Again, all required sub-VIs were provided without the wires connected. As the VI in lab 3 was significantly more complex than VIs encountered to this point, some explanation of the relationship between sub-VIs was needed. Corresponding lectures focused on time and frequency methods of analyzing the data.

Approximately 6 hours of lab time is suggested.

#### Lab 4: Digital Control: Pumps and Constrictors

The fourth lab was designed to aid groups in using LabVIEW to control external devices. Specifically, they were challenged to control a pump and constrictor. As there were many steps in this lab, tasks were divided into four sections. The instructor verified that each section was completed before allowing students to move on to the next section.

##### *Part I: Signal generation*

Students were challenged to:

- Connect the pump to a constant power supply and verify the range of voltages that will drive the pump. For the pumps used in BMEG 350 this range was approximately 2-4V.
- Create a 1Vpp, 0.5Hz rectified sinewave with an offset of 2V within LabVIEW.
- Verify the signal using an oscilloscope
- Send the signal to the pump

Performing the above steps will *not* drive the pump because the DAQ board cannot supply enough current. These findings can be used to motivate a discussion on power requirements of devices.

##### *Part II: Power*

Students were challenged to insert a variable power supply into their system. The input to the variable power supply is the rectified sinewave from LabVIEW and the output is the same voltage signal with amplified current. The result is that the LabVIEW program can now drive the pump.

##### *Part III: Event Driven Programming (Optional)*

The DAQ card used in BMEG350 will hold the last voltage received even after the LabVIEW VI has been stopped. The result is that the pump will remain on even after the VI is stopped. To correct this situation, students were challenged to use Event Driven Programming within LabVIEW. The basic concept is that a VI can be constructed that will adapt its functionality depending upon some variable. As a demonstration of Event Driven Programming, students receive a simple example VI that will shut itself off in one of two cases: 1) the user presses the STOP button or 2) the voltage output is greater than

5V. Student must modify the VI created in parts I and II to shut off if the voltage output is ever greater than 5V or the user presses the stop button. When either condition is met 0V is sent to the DAQ card. It is pointed out that for semester projects, pressure and flow measurements could be used in a similar way to drive different system behaviors.

#### *Part IV: Constrictor Control*

The skills used to control the pump are applied to control a variable constrictor. Students must read the data sheet and decide the best way to integrate the constrictor into their system.

Approximately 6 hours of lab time is suggested. Students should expect to spend significant time outside of class.

#### Lab 5: Introduction to PID controllers

The fifth lab was designed as a qualitative introduction to PID controllers. It requires only a premade LabVIEW VI (i.e. no external devices) and can be effective as an independent lab. The general flow of the VI is to supply the LabVIEW PID controller (part of the control systems toolbox) with a current state and setpoint. The students were challenged to adjust the P, I and D terms as well as the setpoint and observe the following:

- Does the system state always reach the setpoint?
- Are there different ways in which the state reaches the final value?
- How fast does the output reach the final value?
- Determine the optimum values for P I and D for speed and stability
- How might you quantify speed and stability?

Followup lectures focus on the theory underlying PID controllers with parallels made to physiologic control systems (e.g. temperature regulation). It was helpful to remind students of the algorithm they developed in the first lab and have them compare it to the PID controller. Quantitative terms such as overdamped, underdamped, overshoot and undershoot, steady-state error and rise time can be introduced using examples from the qualitative lab. Here again, the instructor is simply attaching names and definitions to phenomenon the students have already observed.

Until this point, inputs to and outputs from LabVIEW have been conducted at the fastest rate the software and hardware could synchronize. A secondary purpose of this lab is to demonstrate how the update timing may be controlled by the user. Students are encouraged to experiment with the timing of the updates and the impact on the PID controller. These experiments can motivate discussion/lecture on delays and lead in to more complex PID controllers such as the Lag-Lead.

Approximately 1-2 hours of lab time is suggested.

#### Lab 6: PID Control of Recirculating Flow Loop

The final vertical lab is meant to bind together the previous five labs. Students are challenged to repeat the first lab (i.e. apply a constriction and adjusting flow rate to return a pressure drop) but now all devices are controlled directly from LabVIEW. Most groups encounter problems in making the jump from Lab five to Lab six. It is at this point that class lecture/discussion can focus on effective troubleshooting, the problems of delays in systems, and tradeoffs in design. It is important for students to have this experience with a reasonably complex system as it provides them with a basis for choosing an appropriate semester project. Those who have chosen a project that is too challenging often realize this and adjust the scope of their project. It is pointed out to all groups that the ability to choose an appropriate project will be an extremely valuable skill when considering future projects (e.g. senior design project).

Approximately 3 hours of lab time is suggested and. Students should expect to spend significant time outside of class.

### **Semester Project**

The vertical labs were designed to build the basic skills needed to complete the semester-long student-driven design project. The physical system constructed in the six vertical labs also served as a starter system that could be modified.

Although students were given the freedom to choose their project topic, they were challenged to scale their project (tube sizes, flow rates, pressure drops) to closely model the real system. Creativity was encouraged and effective use of outside resources (e.g. literature, faculty, lab technicians) was allowed. It was understood, however, that outside resources could not be abused. For example, students could not “hire” someone to do their project for them. As the semester progressed, groups were expected to gain a level of independence from the instructor. This specifically meant making a good effort toward debugging problems before contacting the instructor. If the instructor was contacted, evidence was required that the group had attempted multiple solutions to the problem.

During the course of the semester a number of checkpoints (e.g. assignments, meetings), assisted students in staying on track. At three times during the semester, formal group meetings with the instructor were scheduled to discuss the specifics of each project. Although it was not required, students were encouraged to keep a design log and use it to drive the meetings. Students also were required to turn in a preliminary project proposal early in the semester and a final project proposal later in the semester. Some points that were evaluated in the proposals were:

- Problem statement or hypothesis and biomedical motivation
- Detailed project objectives listed in a hierarchical order
- Sketch and written description of proposed system with additional supplies needed
- Description of experiments to be conducted along with a control experiment
- Any pertinent calculations to be performed and template figures/tables to be filled in
- Weekly timeline for project

Example Project Titles

- “Modeling hypercoagulability: Control system to maintain blood pressure”
- “A system to study gravity induced loss of consciousness”
- “Control of blood pressure in the conjoined region of omphalopagus twins”
- “Vasoconstriction in response to hypothermia”

**Student Assessment**Vertical Lab Assessment

As the instructor completed each vertical lab before the students, there was some assurance that the labs would produce results. It was therefore, possible to grade the vertical labs based on results. The means of assessing results was through written assignments and VIs. Although the focus of the above vertical labs was on the building of technical skills and thought processes, a unique writing approach was believed to enhance the experience. The details of the writing progression have been provided in a separate ASEE paper. Briefly, students were challenged to provide short and focused written descriptions of their results, accompanied by a single graph summarizing their findings.

Project Assessment

Due to the wide variability in the scope of the semester-long project, it was inappropriate to grade entirely on results. Rather, 50% of the project grade was based on process while the remaining 50% was based on results. For the process grade, the focus was on effort, attention to detail, effective troubleshooting and communication of progress. Included in the results grade was a final presentation and final report. The 20-minute final presentation was delivered by the group and included both an oral report on their project and a demonstration of their working system. The two-page report was written in IEEE journal format.

**Course Assessment**

At the completion of the Spring 2006 course, students (n=13) were asked to evaluate their project experiences on a 5-point Likert scale. The instructor also recorded observations on the course. These are summarized below:

Numerical Scores

	Average	STD
I can think of a complicated system as composed of sub-systems that are related by signals	4.67	0.49
The design of an automated system was an effective way to motivate BMEG 350	4.67	0.49
It is important that projects are unique and developed by the groups	4.75	0.45
The project labs prepared our group to design and build our project	4.33	0.65
The semester project has stimulated me to think about senior design	4.23	0.73
I developed better troubleshooting skills by working on a real system	4.58	0.67

The integrated lab and lecture format was helpful	4.83	0.39
Short and focused written assignments were more effective than full lab reports.	4.83	0.39

It should also be noted that course assessment was conducted at the end of the semester. It is the authors' opinion that the evaluations would have been very different if given earlier.

#### Select Student Comments

- “Project was very frustrating, but worked out in the end. You have to walk a fine line between babying us, and answering our LabVIEW questions too quickly, and making us figure it out ourselves, which causes frustration and resentment. I don't envy you.”
- “Non-technical lectures were a great lead-in to the engineering behind it.”
- “I am very pleased with how everything came together at the end. All the concepts and ideas were helpful in our projects. I can think in terms of systems and I can see how this could be useful.”
- “The vertical lab set-up was essential in getting us to learn the multitude of equipment and procedures that were needed for the final project.”
- “I liked the amount of lab time we were given. I would've liked it if my project would've worked. I wish the professor could've given us more feedback and helped with trouble-shooting.”

#### Instructor Observations

- The primary instructor observation was that the course required a great deal of flexibility and communication from both the students and instructor. Problems (either technical or motivational) left unresolved had the potential to cause great frustration. As in most problem-based learning courses, self-learning by the students did not translate into less work for the instructor. In fact, for the course to be successful a very significant investment was necessary from everyone.
- In any open-ended project it is normal, in fact encouraged, for groups to go down paths that are unproductive. While these wrong turns cause some student frustration, it is the instructors' job to point out that wrong turns are a valuable component of real-world engineering. As the semester is only so long, it is also the instructors' responsibility to ensure that groups do not spend too much time going down an unproductive path.
- Students did not always react well when they realized that the instructors would not simply give them answers. Some were also surprised or upset to learn that in some cases the reason the instructor was not providing answers was because they did not know the answer. The most significant frustration (for the instructor and students), however, was faulty equipment. Although most problems were traced back to improper use, there were instances of equipment failure or malfunction. It is recommended that at least one extra set of all equipment is available to ensure that projects do not stall.
- As the semester progressed, it became apparent that material toward the end of the syllabus would not be reached. As the instructor included these topics on the syllabus because they are important signals and systems concepts, there was the temptation to abandon or scale back the vertical labs and project. It was helpful in these moments to

be reminded that material that is “learned” but can’t be applied is not useful to an engineer.

- Although the vertical lab sequence and semester project were motivated by a fluids/transport, the ideas presented could be adapted to other courses such as biomechanics, tissue engineering or bioinstrumentation.

### **Conclusions**

Engineers are often thought of as applied scientists. Although this is not incorrect, the educational impact of this view is that students with strong math and science skills are expected to succeed as engineers. In fact these skills are only the prerequisites of a competent engineer. To be effective, engineers must be able to translate and adapt their knowledge and skills to new situations. It is difficult for students to learn this ability through a combination of lecture, homework and instructor-designed labs. It is our students’ ability to creatively solve problems that make them desirable to future employers and ensure their success throughout their careers. The caveat is that learning how to navigate a novel problem cannot be taught; it must be experienced and practiced.

Based upon student feedback and instructor observations, we believe the concept of vertical labs leading toward a semester-long project was an effective way for students to learn and apply concepts taught in a traditional signals and system courses. Student were able to effectively translate course work to design, developed intuition in troubleshooting, and had many opportunities to encounter open-ended problems that required a creative solution. While these skills do not always come easily, in the authors’ experiences, students, when motivated, rise to the occasion. As the instructor, the sequence provided countless teachable moments that would not have developed in a traditional course.

### **References**

Richerson SJ and Cavanagh DP “Vertical Laboratories: Within Biomedical Engineering Courses and Across the Curriculum”, Proceedings of ASEE 2005.

Cavanagh DP and Richerson SJ, “An Integrated Lecture-Lab Approach for an Introduction to Biomedical Engineering Course”. BMES 2004.

Tranquillo, J, “Qualitative, Quantitative, Open-ended Design: A Progression in Laboratory/Lecture Learning”. Proceedings of ASEE 2006.

**Appendix: Nuts and Bolts**

Each group had 24 hour access to the following equipment:

Analog Equipment

Masterflex L/S pump (77200-60)  
Cole Palmer Rotameter (10850)  
Assorted Tubing and Connectors  
Keck Ramp Clamp (C-06835-07)  
Omega Pressure Gauges (DPG100B-15G)  
Cole Palmer Pulse Dampener (C-07596-20)

Digital Equipment

Greylor Dynesco Pump (PW-12DC)  
McMillan 111 Flo-Meters  
AALBorg variable solenoid valve (PSV-5) and driver (PSV-D)  
Honeywell ASCX05DN pressure transducers  
Labview 8.0 with controls toolbox  
Keithley KPCMCIA-16AIAO-C DAQ Card  
Keithley STP-37 screw terminal  
Agilent 33120A Function Generator  
Agilent E3631A Constant Power Supply  
Custom built 10A,  $\pm 24V$  Variable Power Supply  
Agilent 54624A Oscilloscope