Bioinstrumentation: A Project-Based Engineering Course

Aaron M. Kyle, Member, IEEE, David C. Jangraw, Matthew B. Bouchard, and Matthew E. Downs

Abstract—This paper presents the development, implementation, and assessment of a project-based Bioinstrumentation course. All course lectures and hands-on laboratory activities are related to a central project theme: a cardiac pacemaker. The students create a benchtop cardiac pacemaker by applying instrumentation knowledge acquired in the course to each stage of device development. This approach emphasizes both conceptual and practical student learning: The students must apply theory learned in the course to create their devices. Indirect and direct assessment performed with respect to the major course objective demonstrated that course participants were able to successfully design, construct, and test a bioinstrumentation system. The students perceived a marked increase in their instrumentation knowledge, objectively corroborated by their performance on specific exercises related to the creation of their benchtop pacemakers. The outcomes of the course development presented here, along with the course structure and pedagogical methodology, may enhance engineering education by acting as a guideline for the creation of courses in which a central project theme is used as a platform for concept instruction.

Index Terms—Bioinstrumentation, biomedical electronics, biomedical engineering education, biomedical measurement, project-based learning.

I. INTRODUCTION

The advent of project-based learning in engineering disciplines has provided a plethora of opportunities for enhancing skills and educational experiences for students [1]–[7]. This is particularly true within the highly interdisciplinary field of biomedical engineering (BME), whose undergraduate students are often called upon to apply newly acquired knowledge from a variety of fields [8]–[10]. An area within BME particularly appropriate for project-based learning is bioinstrumentation, i.e., the practical use of basic electronics, signal acquisition and processing tools, and computer programming for biomedical needs. BME students need instrumentation design skills comparable to those of their peers in more traditional engineering disciplines to be able to complete advanced projects (such as senior design projects) and to succeed post-graduation in competitive careers in industry or academia. Bioinstrumentation has classically been taught through introductory electrical engineering courses whose concepts are subsequently applied to biomedical devices, or through hybrid courses where electrical engineering concepts are taught in the context of biomedical devices and/or models [11]–[16]. Here, a novel project-based course is presented that provides bioinstrumentation instruction by combining a central project theme with teaching of fundamental instrumentation concepts.

Students in this course learn bioinstrumentation in the context of a model system: a cardiac pacemaker (PM) that includes sensing and stimulation, processor-based acquisition, and feedback control. Students use basic circuit theory, electronics, and real-time control software integrated with the hardware to create an emulated version of a cardiac pacemaker. The focus on a single device model system employs elements of project-based learning and uses the “spiral learning” method, in which a class repeatedly revisits a problem after gaining additional expertise, to reinforce concepts, increase students’ investment in their work, and develop a robust problem-solving methodology [4], [17].

This paper describes the structure and development of the course and the results of indirect and direct assessment of students’ mastery of the core competencies and the efficacy of the course model.

II. INSTRUCTIONAL MATERIALS AND ASSESSMENT METHODOLOGY

The Bioinstrumentation course emphasizes learning through lectures, hands-on laboratory activities, and open-ended design challenges. The course objectives are for students to do the following:

1) design, test, and implement analog circuitry to measure and condition biomedical signals, and to actuate tissues;
2) develop control code (using MATLAB or a microcontroller) to acquire and digitize signals of interest;
3) design and implement algorithms that conduct near-real-time analysis and make decisions with respect to the acquired signals;
4) verify and validate the emulated pacemaker’s performance in a living system: a Xenopus frog.

A. Course Structure and Pedagogy

The three-credit Bioinstrumentation course consists of one lecture and one laboratory session each week. Each 75-min lecture is structured to provide a theoretical overview of the major instrumentation concepts via interactive activities and to encourage student participation through concept discussion and in-class exercises. The weekly laboratory sessions, each 2 and 3/4 h long, provide hands-on learning and an opportunity for students, working in three- or four-person teams, to apply the
Students are introduced to the use of amplifiers for active filtering of operational amplifier circuits for signal measurement. They design and build the front-end signal conditioning circuitry to measure the cardiac electrogram. The students write MATLAB acquisition code to digitize and display the signal. This code is subsequently included in student-designed graphical user interfaces (GUIs). They adjust the cutoffs of their analog filters from the first module, then derive the empirical electrical current strength-duration curve [19]. These data inform the stimulation circuitry created in Module V.

In Module IV, students are introduced to microcontrollers to better represent the acquisition and control scheme that might be found in an actual implantable pacemaker. The students transition to using an Arduino microcontroller, instead of MATLAB and a PC, to perform the benchtop pacemaker’s data acquisition and computations. They use the Arduino to digitize the cardiac electrogram circuit output from the first module, and modify the Arduino control code to emulate the functionality of a ventricle stimulating, ventricle sensing, inhibitory (VVI) pacemaker.

Module V focuses on building stimulatory circuits to electrically excite the myocardium. Students receive instruction on the basics of semiconductors, with a focus on the use of BJTs to create pulse generation circuitry. The duration and intensity of stimuli must be sufficient to elicit myocardial contractions as determined in Module III. The circuit is triggered by a digital output from the Arduino in response to an arrhythmic event.

During Module VI, the final portion of the class, students combine the components developed in the previous modules into a single PM system capable of sensing cardiac electrical activity, digitizing the signal, evaluating whether the desired heart rate is achieved, and triggering the stimulatory circuitry to deliver a pulse in response to an arrhythmic event. They must also add a further functionality of their choice. The benchtop PM development culminates with its testing on Xenopus frogs.

### C. Student Performance Assessment

Student course performance is assessed by the following:

- final presentation and demo (15%);
- midterm practical (20%);
- final design challenge (10%);
- peer assessment (5%).

The lab reports include Abstract and Introduction, Materials and Methods, Results, and Discussion sections. This reporting format is meant to engage students to consider their instrumentation design in the broader context of its application to the benchtop PM.

The midterm examination is a combination of written and laboratory exercises focused on basic circuitry and biosignal measurement. Each student is assigned a laboratory station and allotted 45 min to complete a set of exercises in designing, constructing, and evaluating basic circuitry. The practical format facilitates evaluation of individuals’ bioinstrumentation skills.

Each laboratory team is required to demonstrate their PM’s performance, showing: 1) that their device can function in the VVI mode at a prescribed heart rate; and 2) that their added functionality works. These demonstrations reveal how students have synthesized their knowledge of bioinstrumentation and cardiac PMs.

The final demonstration of students’ understanding of bioinstrumentation is the Final Design Challenge. In this challenge, each student identifies a pathology that requires an electro-stimulatory device solution. In addition to describing the underlying

<table>
<thead>
<tr>
<th>Module</th>
<th>Topic(s)</th>
<th>PM Component</th>
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<tbody>
<tr>
<td>I</td>
<td>Analog Circuit (Sensing)</td>
<td>Cardiac Electrogram</td>
</tr>
<tr>
<td>II</td>
<td>Principles of Digitization, A/D Conversion</td>
<td>Electrogram Digitization Hardware</td>
</tr>
<tr>
<td>III</td>
<td>Anatomy and Electrophysiology</td>
<td>Excitable Tissue Characterization</td>
</tr>
<tr>
<td>IV</td>
<td>Advanced Programming</td>
<td>PM Control Algorithm</td>
</tr>
<tr>
<td>V</td>
<td>Stimulation Circuitry</td>
<td>Cardiac Tissue Stimulation</td>
</tr>
<tr>
<td>VI</td>
<td>Additional PM Functions</td>
<td>PM Integration and Final Testing</td>
</tr>
</tbody>
</table>

TABLE I

BIOINSTRUMENTATION COURSE MODULES AND ASSOCIATED CONTENT
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TABLE II

<table>
<thead>
<tr>
<th>Course Objective</th>
<th>Course Component</th>
<th>Description</th>
<th>Mean % Score ± Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>i (Analog Circuits)</td>
<td>Module I</td>
<td>Image of ECG and comparator circuit output</td>
<td>100 ± 0</td>
</tr>
<tr>
<td></td>
<td>Module I</td>
<td>Image of ECG measured from human subject</td>
<td>100 ± 0</td>
</tr>
<tr>
<td></td>
<td>Module II</td>
<td>Digital high readings from electrogram comparator</td>
<td>94 ± 14</td>
</tr>
<tr>
<td></td>
<td>Mod V</td>
<td>Monophasic pulses from transistor circuity</td>
<td>72 ± 39</td>
</tr>
<tr>
<td></td>
<td>Final Presentation – Design</td>
<td>Explanation of benchtop PM, hardware components</td>
<td>83 ± 15</td>
</tr>
<tr>
<td></td>
<td>Midterm Practical</td>
<td>Determine cutoff frequency, design signal acquisition channel</td>
<td>87 ± 3</td>
</tr>
<tr>
<td></td>
<td>Final Challenge – Design</td>
<td>Description of blocks of proposed solution</td>
<td>87 ± 18</td>
</tr>
<tr>
<td>ii (Control Code)</td>
<td>Module II</td>
<td>Demonstration of electrogram acquisition GUI</td>
<td>93 ± 14</td>
</tr>
<tr>
<td></td>
<td>Module II</td>
<td>Demonstration of strength-duration curve GUI</td>
<td>88 ± 13</td>
</tr>
<tr>
<td></td>
<td>Module IV</td>
<td>Multichannel acquisition of simulated ECG</td>
<td>95 ± 10</td>
</tr>
<tr>
<td></td>
<td>Final Presentation – Design</td>
<td>Explanation of benchtop PM, microcontroller and digitization</td>
<td>84 ± 15</td>
</tr>
<tr>
<td>iii (Algorithms)</td>
<td>Module IV</td>
<td>Description of VVI pacing method</td>
<td>93 ± 14</td>
</tr>
<tr>
<td></td>
<td>Final Presentation – Design</td>
<td>Illustrative screenshot, demonstrating VVI efficacy</td>
<td>87 ± 17</td>
</tr>
<tr>
<td>iv (Complete PM)</td>
<td>Mod III</td>
<td>Plot of current S-D curve w/ rheobase and chronaxie</td>
<td>100 ± 0</td>
</tr>
<tr>
<td></td>
<td>Final Pres. – Testing</td>
<td>Pace at desired rate for 60s, additional functionality</td>
<td>92 ± 14</td>
</tr>
</tbody>
</table>

pathophysiology, the students provide a high-level design of a device to address the problem. Problems addressed by students in the 2014 course offering include: functional electrical stimulators, deep brain stimulators for Parkinson’s disease, and vagus nerve stimulation for treatment of epilepsy.

Peer assessment is conducted at midterm and at the end of term using the Comprehensive Assessment of Team Member Effectiveness (CATME) peer evaluation tools [20].

D. Course Assessment

1) Direct Assessment: Student progress and course model efficacy were evaluated via exercises related to building the benchtop PM. Direct course assessment was conducted using Point of Learning (PoL) exercises embedded within graded materials. For example, in Module V (Stimulation Circuitry), students design a circuit that can produce a monophasic pulse at a prescribed amplitude and duration. The PoL exercise requires the students to demonstrate that the pulse output can be delivered to a resistive load meant to emulate the electrode-epicardium interface (see Table II). To quantify performance with respect to the outcomes, certain PoL problems were identified and mapped to the course objectives. These PoL problems were identified at the end of the course to avoid bias in grading.

2) Indirect Assessment: The indirect assessment data were obtained through pre- and post-course surveys, whose responses were on a five-point Likert scale (1—Strongly Disagree to 5—Strongly Agree). The pre-course survey was used to evaluate students’ existing instrumentation knowledge and to tailor instruction accordingly. Comparison of the responses from the pre- and post-course surveys allowed a summative assessment of students’ perception of their improvement in their instrumentation skills.

Formative assessment was achieved via surveys administered throughout the term. An online survey was sent out after each module, inquiring about comprehension of the concepts, level of preparation for the module, understanding of how the module contributed to understanding of bioinstrumentation and the role of the particular module in the function of a cardiac PM.

3) Analysis of Outcomes: The pre- and post-course surveys were statistically assessed using a Wilcoxon Rank Sum test (α = 0.05). These comparisons were performed to determine if there was significant improvement in student-perceived skills attributable to the course. If a skill’s median post-course survey score was significantly greater than the pre-survey score—and students’ post-course survey score indicated that they agreed or strongly agreed (score of 4 or 5) with the statement of positive achievement—then it was concluded that the goal was achieved. For the individual module surveys, questions that were common for each module were compared. Wilcoxon Signed Rank tests (α = 0.05) were performed, comparing the mean student responses to the neutral statement score (score of 3). The module outcomes were considered successfully achieved when scores were significantly greater than the neutral score.

For direct assessment from PoL problems, student scores were normalized and averaged to evaluate performance with respect to course objectives. A mean score above 70% was indicative successful mastery of the concepts.

III. RESULTS

A. Course Participants

The first offering of the Bioinstrumentation course took place in the Spring semester of 2014. It was approved as a 4000-level class (open to undergraduate and graduate students) cross-listed within the Departments of Electrical and Biomedical Engineering at Columbia University, New York, NY, USA. The available laboratory facilities constrained the number of participants to 24 students; the course quickly filled to maximum capacity. A demographic breakdown of course participants by level and discipline is provided in Fig. 1.

B. Observations From First Course Offering

1) Laboratory: The labs had the shared goals of giving students experience in the practical design of instrumentation components, and of building the various module components of the
benchtop PMs. Although they had completed the pre-lab activities, it was routinely observed that students did not have a comprehensive understanding of the procedures prior to class, which often resulted in extensive consultation with the instructors for clarification. Questions about basic circuitry practices came up as frequently as did conceptual bioinstrumentation questions, implying that despite their prior experience in circuit course(s), students were still deficient in their practical lab skills. Despite this limitation, all groups successfully completed the procedures and lab design challenges. In terms of time spent in the lab, most groups exceeded the allotted 165-min periods during the first two modules. This is likely attributable to the dense nature of these initial modules as well as to students (re-)familiarizing themselves with basic circuitry concepts and troubleshooting. In Modules III–V, the time required better aligned with the class periods. In Module VI, students often required an extra one or two hours per week to complete their devices. Students reported an average of 3.69 h per week outside of class time spent on each procedure.

2) Lab Challenges and Final PM Design: Each Design Challenge had the students build one discrete component of a cardiac pacemaker. All student teams were able to successfully create these PM elements and then integrate them to form the final prototype. As mentioned, students had to incorporate an additional functionality for their benchtop PM; this was intended to challenge the students: 1) to learn more about the practical capabilities of a cardiac PM; and 2) to use their instrumentation knowledge to create a PM component of their design. Suggested PM functionalities were primarily derived from [18] or from independent research. The added functionalities produced during the inaugural course offering included blanking circuitry, temperature monitoring, automated strength-duration measurement, and electrode impedance sensing.

C. Course Assessment

1) Direct Assessment: Direct course assessment evaluated student performance on PoL problems culled from the lab procedures, the midterm practical, and the final design challenge. The students’ performance (% of total points available) on specific PoL problems is provided in Table II.

The students exhibited the desired level of competency (mean scores exceeding 70%) on all of the PoL evaluation problems, demonstrating mastery of the major course objectives. While the majority of the PoL problems were drawn from group exercises in the laboratory procedures, performance on exercises from the midterm practical or the final design challenge provide insight into students’ individual skills. As with the trend observed in the team PoL problems, individual students also displayed mastery of concepts. It is particularly encouraging that the performances were strong on the final Design Challenge (Module VI, incorporating the additional functionality), demonstrating not only conceptual understanding, but the ability to apply the concepts to novel problems. An implicit goal of the course is to empower students with instrumentation skills with application beyond the challenges of the class. Demonstration of aptitude in the module and final design challenges represents successful achievement of this goal.

2) Indirect Assessment: Indirect course assessment was conducted via responses to the following common survey questions administered at the end of each module.

• The background material in the lab procedure was useful and contributed to my overall understanding.
• The lecture contributed to my overall understanding of the module content.
• I understand how this module’s content contributes to the overall design of my benchtop pacemaker.
• The module contributed to my understanding of bioinstrumentation design.

Compiled student responses to these questions are presented in Fig. 2. Students generally responded affirmatively to the queries, indicating that the module content contributed to their overall learning. The students appreciated the modules and their contribution to the formation of a benchtop PM and understood why the content was important for bioinstrumentation training. Overall, these results show that the concepts imparted in each of the modules contributed to the students’ sense of perceived learning.

Pre- and post-course surveys were administered in order to quantify the student-perceived improvement as a result of the class. In the pre- and post-surveys, students were asked to rate the extent to which they agreed with statements including the following.

A) I am interested in circuit design, signal acquisition, and bioinstrumentation.
B) I am knowledgeable of the form and function of cardiac pacemakers.
C) I am able to design, test, and troubleshoot electrical sensing and actuation circuitry.
D) I am able to design, test, and troubleshoot MATLAB software.
E) I am able to write code for and make use of a microcontroller (Arduino).
F) I know how to test and debug a complete bioinstrumentation system.

The compiled results of the pre- and post-course surveys are displayed in Fig. 3. It does not appear that the rigorous nature of
the course adversely effected students' interest in bioinstrumentation. The students reported an increase in bioinstrumentation knowledge, satisfying the four course objectives and the overall purpose of this class. In the majority of the categories related to explicit skills attained, there were marked improvements in students' perception, mirroring the observations from the PoL evaluations. The most evident improvements were in the circuitry design and microprocessor categories. This outcome was not unexpected. The majority of the course participants, while having prior circuits knowledge, did not have a project-based experience emphasizing practical circuitry design. The material covered in this course likely solidified existing knowledge while introducing novel, practical skill sets. The majority of the course participants had not received formal instruction in microcontrollers. The training provided in this course, coupled with the opportunity to apply newfound knowledge to controller tasks necessary for the PM operation, resulted in an increase in actual and perceived skills in microcontroller use. These indirect results provide strong evidence that the students learned the concepts imparted in this course.

IV. DISCUSSION AND FUTURE WORK

This course establishes a novel paradigm for instruction in bioinstrumentation that emphasizes project-based learning in coordination with conceptual knowledge. While many courses teach comparable skills, the decomposition of an existing biomedical device into modular blocks creates practical platforms for instruction. A strength of the methods used here is the emphasis on project-based educational approaches without sacrificing conceptual learning, as evidenced by the students' performance and their successful creation of a pacemaker that successfully paced a frog heart.

Through the combination of theoretical teaching and the emphasis on applying concepts to a central project theme, the course participants were able to increase their knowledge in circuitry, acquisition and processing systems, and electronics. The central thesis in devising this course was that the focus on a project theme would increase student comprehension of concepts and facilitate synthesis of course materials. Student performance on PoL exercises as well as self-reporting corroborates these assertions. The vast majority of the class both demonstrated and felt that their instrumentation skills were improved through participation. While these initial results are highly encouraging, the authors concede that the true test of whether these skills are enhanced will be in what the students accomplish beyond the scope of this course. Post-course efficacy may be assessed through follow-up surveys.

The course was designed for undergraduate students, particularly BME Juniors and Seniors. Interestingly, the majority of the course participants were M.S. students. It was initially anticipated that the content would be too basic for graduate students. However, it was quickly discovered, through feedback and performance, that the instruction in basic electrical engineering concepts remediation was appropriate, even for the more advanced students in the class. The authors hypothesize that the students welcomed the reintroduction of concepts because of the applied manner in which the material was conveyed. The structure of this course afforded the participants a holistic view of instrumentation along with the opportunity to apply their designed circuitry to measure and actuate a living system. The students’ synthesis of knowledge was perhaps best evidenced through their ability to apply course concepts in the creation of an additional PM functionality. Finally, the students found this course to be an enriching educational experience. From the post-course evaluation, one student identified Bioinstrumentation as “the best class I’ve taken at Columbia—by a long shot. It’s been a lot of work, but I feel the material I’ve learned is highly valuable and pertinent to the field of biomedical device design.”

There are opportunities for course improvement. The PM functions were taught in a fundamental fashion. That is, a pacemaker is a bio-electrical sensing/stimulating device that may administer excitatory shocks in response to arrhythmic events. While this interpretation is basically correct, it is a significant simplification of what actual PMs do. One of the major calls from the inaugural course participants was for increased discussion of real PMs and their functionalities. Much of the design of PMs may be proprietary or outside the scope of the
class, but there are opportunities for advanced discussions of real-world devices. The authors are considering inviting guest instructors with extensive PM design experience to speak to the course participants about real-world PM design. These experts might also be called upon to evaluate the student designs as well as the overall technical content, effectively acting as industry advisors. This oversight may enhance course participants’ preparation for real-world biomedical instrumentation design.

This course presents an excellent opportunity to employ a flipped classroom instructional model. This will allow students to explore the concepts at their own pace or in a repeated fashion. Lecture time would be used to elaborate on concepts via exercises and discuss practical considerations of the benchtop PM design, creating opportunities for problem-based learning [1]. This approach may further augment the course’s focus on the practical instrumentation design.

Perhaps the most exciting outcome of this course development is the use of a paradigm that emphasizes conceptual knowledge in the context of a central project theme. Rather than creating artificial demarcations between theory and practice, the modular approach facilitates learning in parallel with application. The single-device instructional model is particularly useful for biomedical engineering students. The multitude of topics covered in BME curricula often results in students with a broad knowledge base, often at an expense of profound knowledge in particular topic areas. By emphasizing a single project theme, this course model emphasizes profound bioinstrumentation knowledge, allowing students from BME and other disciplines to attain depth of understanding. To encourage other institutions, particularly BME departments, to embrace this approach, the authors will readily disseminate course materials upon request.

The approaches presented herein can be viewed as a framework for the implementation of project-based learning philosophy. With respect to a cardiac PM, a variety of project-centric courses or modules could be created. If a course were focused on biomaterials, the enclosure of the PM’s generator, lead and insulation materials, and electrodes could be intensively examined in the contexts of materials’ properties and their interactions with living tissues. Beyond a pacemaker, this course model could be applied to other implantable or electro-stimulatory devices, joint implants, or even drug delivery systems. A similar instructional approach can be readily applied to a broad variety of engineering areas. In summary, this approach provides highly exciting instructional platforms for both teachers and students, promoting essential conceptual knowledge in coordination with practical considerations that are crucial for real-world engineering.

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REFERENCES


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Dr. Jangraw is a member of the engineering honor society Tau Beta Pi, received an honorable mention for the NSF Graduate Research Fellowship, and was a finalist for Columbia University’s Presidential Award for Outstanding Teaching by a Graduate Student.

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