A Biosignal Acquisition and Conditioning Board as a Cross-Course Senior Design Project

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***Abstract*—In a single-semester course that incorporates both lecture and design, time constraints make it difficult to provide students with a substantive design experience that addresses multiple system elements. This paper presents a design experience that addressed numerous facets of a biomedical signal acquisition system by merging design credits for two undergraduate, senior-level courses: *EECE 773 – Bioinstrumentation Design Laboratory* and *EECE 628 – Electronic Instrumentation*. The innovative effort joined the sensor circuitry and signal display elements of a bioinstrumentation course with the data acquisition and serial communication topics often taught in electronic instrumentation courses. The overall goals of this project were to (a) create a substantial, design-driven learning experience for electrical engineering seniors and (b) increase student interest by attaching a biomedical context to an instrumentation project that would otherwise be generic. These goals were supported by 11 learning objectives that address clinical context, project planning, project roles, signal conditioning, signal management, printed circuit board development, biomedical data display, and written communication.**

In the initial project offering, 18 students were divided into three teams, each of which designed and built a system to acquire, process, and display data from multiple biomedical sensors, where the signal conditioning functionality for each sensor was remotely programmable. Each acquisition board communicated with a custom LabVIEW interface via a Universal Serial Bus link. Development foci for each team changed over time as technical choices led to unexpected design complexities. Assessment of the experience was provided via a post-project survey that addressed the 11 learning objectives, learning in 16 technical areas, interpersonal team dynamics, and project administration. Survey results mirrored informal student comments: while this effort required a substantial time commitment relative to a typical course project, the learning and satisfaction derived were worth the investment.

Keywords—**Biomedical instrumentation, biosignals, capstone design, data acquisition, engineering education, programmable analog signal conditioning, reconfigurable filters**

I. Introduction

A. Motivation

Hands-on design experiences for senior-level undergraduate students offer a more in-depth learning experience when compared to traditional lecture and laboratory courses. They also provide faculty a means to more fully assess prior learning in students whose transcripts state they have 'learned' material in earlier courses. The value of these experiences is emphasized by ABET Inc. (formerly the Accreditation Board for Engineering and Technology) [1] through the requirement that senior capstone design experiences be incorporated into ABET-accredited curricula.

Kansas State University (KSU) undergraduate Electrical Engineering (EE) and Computer Engineering (CMPEN) curricula therefore focus on developing student competence and independence in the laboratory given that strong laboratory toolsets map to strong design skills. Recognizing the importance of communities and teams in engineering culture, the KSU Department of Electrical & Computer Engineering [2] emphasizes teamwork on projects and laboratory exercises. Experience reveals that some students can "ride along" given contributions of capable teammates, completing a degree while lacking in essential skills. It is therefore crucial to define team roles and assessment methods that address the development of an individual within a team.

B. Course Descriptions

EECE 773 – Bioinstrumentation Design Laboratory (1 hour) is a required senior-level design course for KSU EE students enrolled in the Regents-approved Bioengineering Option. This course is a co-requisite to *EECE 772 – Bioinstrumentation Lecture* (2 hours) and *AP 773 – Bioinstrumentation Laboratory* (1 hour), a course pair also offered to upper-level undergraduate and graduate students in non-EE curricula [3]. The courses address biomedical sensors, biomedical signals, instrumentation, computer-based data acquisition, and medical imaging. In EECE 773, students work in teams to develop sensor-based systems that acquire, process, and display health monitoring data. Each system must incorporate (a) one or more sensors, (b) signal conditioning circuitry and processing algorithms, (c) computer-based data acquisition, (d) a graphical data display and user interface, and (e) a strong design element. Project tasks include (a) a project definition and literature search, (b) a project plan, (c) a design review, and (d) a final project report and demonstration/presentation.

EECE 628 – Electronic Instrumentation (3 hours) is a senior-level design course taken as a technical elective. The course addresses topics like signal transduction, analog signal conditioning, analog-to-digital (A/D) (and digital-to-analog (D/A)) conversion, computer-based data acquisition, filters, sample & hold circuitry, aliasing, and instrumentation amplifiers. In recent offerings, 1.5 credit hours mapped to lecture and laboratory material, whereas 1.5 credit hours mapped to design. To this end, the first half of each semester usually requires four, two-week laboratory experiments where students work alone to develop sub-circuits that are later integrated into complete data-acquisition systems. Because students enter this course with diverse skill sets, early-semester activities incrementally progress from a completely specified exercise to an open-ended experiment requiring a student-designed procedure. This progression and the requisite individual attention ensure that students attain the skills necessary to contribute to a larger team project. The second half of each semester is then dedicated to small-team efforts, where elements of this larger design project relate directly to activities of prior weeks. By this point, individual students feel they have developed specific competencies and realize that effective teamwork requires each team member to bring something to the table. Student evaluation comments reflect satisfaction with their resulting personal growth.

C. Motivation for Merging the Course Projects

When a single-semester course contains 1 or 1.5 design credit hours, an instructor must be creative to define a substantive experience. Early in Fall 2006, the authors realized that each student enrolled in EECE 773 (6 students) was also enrolled in EECE 628 (16 students). By joining these design credits into a 2.5-credit project, students could receive a more substantive design experience in an application area with clear societal benefit. This promoted joint work between students in different EE and CMPEN emphasis areas. Fig. 1 depicts this diverse set of course participants.

Fig. 1. Participants in the cross-course design experience.

II. METHODOLOGY

A. Brief Project Description

The goal of this team project was to design, build, and demonstrate a biomedical signal acquisition board that incorporates programmable analog signal conditioning circuitry tunable over an appropriate frequency range. Acquired biomedical sensor data would be sent to a personal computer over a Universal Serial Bus (USB) interface [4] then processed and visualized with LabVIEW [5].

B. Learning Objectives

This project supported 11 learning objectives that were assessed via written reports, end-of-semester surveys, design reviews, and informal faculty-student interactions. These learning objectives, listed in Table 1 in Section *III. Results & Discussion*, take the following form: "Upon completion of this project, team members should be able to …"

C. Sensor, Board, and Interface Requirements

The system, depicted functionally in Fig. 2, was to be comprised of up to two biomedical sensors, a conditioning and acquisition board, and a LabVIEW interface. Each board channel required an instrumentation amplifier, an electrical isolation stage, a signal conditioning block, and a sample-and-hold circuit. The microcontroller would perform A/D conversion on each signal then forward the digital data serially to a chip that supports USB communication with a host PC, where a LabVIEW interface would process and present these data. The signal conditioning settings (amplifier gains, operating parameters, and filter configurations – cascades of lowpass, highpass, bandpass, and band-reject filters) would be programmable [6] given user selections in the LabVIEW interface. Code sequences representing these selections would be sent to the microcontroller, which would digitally control switches to set filter parameters. As the project evolved, hardware/software constraints dictated updates to the *initial* functional block diagram presented in Fig. 2 (see Section *III. Results & Discussion*).

D. Design Approach

Each team performed a literature search, developed a project management plan, designed the Fig. 2 elements, populated a printed circuit board (PCB), demonstrated the product, and wrote a formal report that archived the process and contained hardware and software reference material. Project plans guided student work and kept students accountable for deadlines. Each project Gant chart included a calendar, task list, precedence relationships, time estimates, person-loading, milestones, design reviews, and the final presentation/report. Students were instructed to establish intra-group contacts, share schedules, identify skills and interests, and select someone to manage the project plan and to generate progress reports. The project was divided into six technical activities:

1. select, characterize, and apply the biomedical sensors,
2. configure, prototype, test, and control the programmable analog circuitry,
3. program the microcontroller and the USB interface,
4. lay out and construct the PCB,
5. create the LabVIEW interface, generate control signals, and provide the PC USB interface, and
6. integrate and test the overall system.

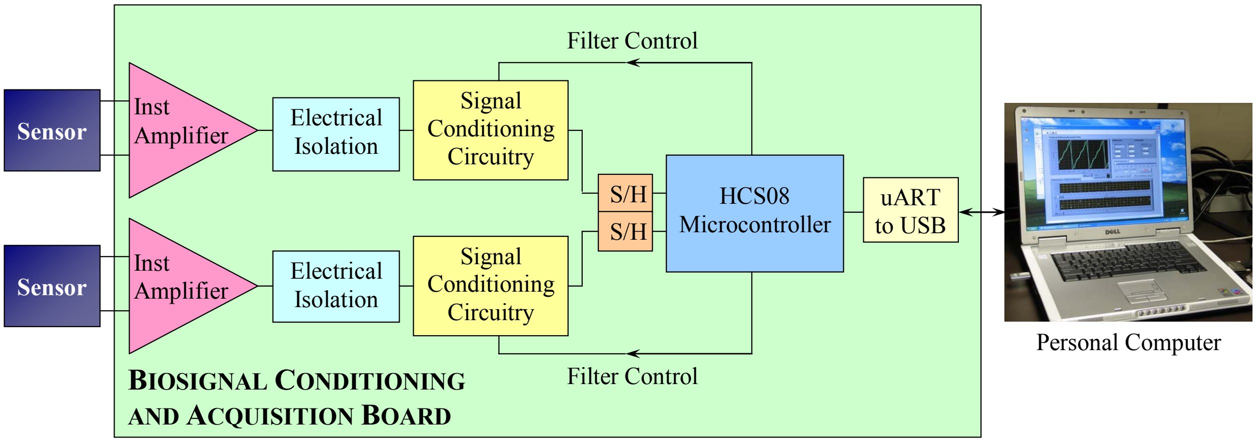

Fig. 2. Initial functional diagram for the biosignal conditioning and acquisition board.

Students worked in sub-teams, and overlap between tasks required coordination of activities and design specifications.

LabVIEW programming was new to most of these students, so National Instruments supported LabVIEW tutorials facilitated by the National Instruments student liaison to KSU. Board layout and routing were accomplished with ExpressPCB software [7], and ExpressPCB services created two-sided circuit boards on FR–4 material. The teams chose these sensors to demonstrate their board functionality:

- Group 1: Electrode pair to provide a signal for a galvanic skin response meter (i.e., stress or lie detector)
- Group 2: Electrode pair for auditory evoked potentials
- Group 3: Piezoelectric pulse plethysmograph for finger tip pressure (blood volume) changes and heart rate [8]

E. End-of-Semester Assessment Surveys

Surveys recorded student perceptions of learning, tallied project elements that students liked/disliked, and archived suggested project improvements. Survey results are listed and discussed in the next section.

III. RESULTS & DISCUSSION

A. Student Design Products

While the project was a substantial undertaking given the constraints of a single semester, the teams were able to demonstrate functional boards. Fig. 3 depicts a student from Group 3 using the fingertip pulse plethysmograph. The inset shows a typical signal received from the sensor and displayed on the LabVIEW interface. A lowpass filter with a 3 Hz cutoff frequency conditioned this signal. Fig. 4 displays the Group 3 hardware board, illustrating the complexity of the analog/digital circuit layout. Final implementations of these boards were relatively sophisticated when compared to the initial functional block diagram in Fig 2.

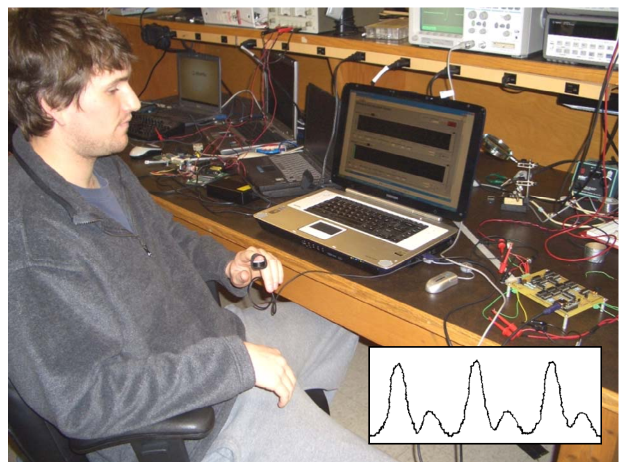

Fig. 3. Group 3 student using a biosignal acquisition board with a finger-worn pulse plethysmograph.

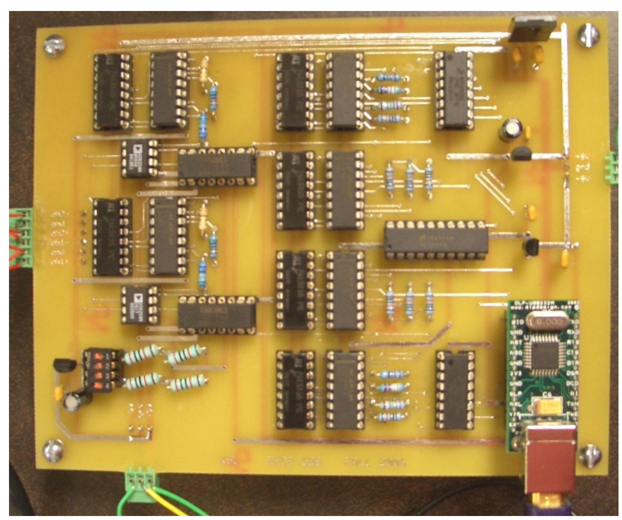

Fig. 4. Group 3 biosignal acquisition board.

B. Technical Issues: Evolution of a Design

As expected, the project grew in scope and complexity through the semester, primarily due to the ongoing discovery of technical problems that required more complex solutions. Increasing complexity also came from change orders generated by the instructors as the projects progressed. These solution ideas were shared among the groups as they materialized, though the teams continued to apply unique approaches to other design hurdles in other areas.

The instructors originally intended each team to develop an analog signal conditioning board linked to a data acquisition (DAQ) card already compatible with LabVIEW on a PC. Since computer-controlled analog signal conditioning is a topic without mature solutions, this area was chosen to be a part of the board design. The resultant design would then include amplifiers and operational amplifier-based filters that could be tuned and reconfigured with digital control signals provided by DAQ output ports. Filter tuning would be accomplished by the simple switching of component values and by the use of variable-frequency, switched-capacitor techniques to change equivalent resistances.

As the desired filter configurations, tuning options, and generated frequencies grew, it became clear that the DAQ-card-generated signals would need to be encoded. The instructors therefore decided to add a microcontroller to intercept and interpret control signals and to coordinate on-board events. The students already had experience with Motorola 68HC11 microcontrollers through *EECE 431 – Microcontrollers* (taken by all KSU EE and CMPEN students), but the Fall 2006 EECE 431 course had migrated to the Freescale MC9S08QG8(CPB) microcontroller (HS08 core), so enthusiasm existed to learn about the capabilities of the new chip. The Freescale microcontroller offers four A/D channels, a timer/pulse-width modulator (TPWM) that could generate a clock for the programmable signal conditioning circuitry, serial peripheral interface (SPI) support to control latches, and serial communication interface (SCI) support to send serial data to a host PC. A sensible design would utilize this A/D capability and simply transmit a digital signal stream to the host PC via a direct USB link. Since time constraints placed the USB protocols and communication timings beyond the scope of the course, a commercial converter chip (DLP Design DLP-USB232M-G USB – SERIAL UART Interface Module) was designed into the system.

Eliminating the DAQ card meant the inclusion of instrumentation amplifiers on the new board. Isolation amplifiers were added for safety, and sample-and-hold chips were coupled with the A/D conversion pins. The number of microcontroller pins were limited (16), so some pins had to serve several functions (e.g., TPWM, SPI, and/or SCI support as noted earlier), further complicating the design. This resulted in creative ways to share pins, finally dictating the use of a second microcontroller. Each design team arranged the two microcontrollers in a master-slave configuration; the master microcontroller provided A/D conversion and communications, while the slave microcontroller generated and coordinated control signals. This brief summary hints at the magnitude of the design work accomplished by the students.

C. Student Survey Results

The first two survey elements (Tables 1 and 2) addressed project learning objectives and technical areas. *In Tables 1 and 2, the "Pre" and "Post" columns represent student perceptions of their comfort and proficiency before and after the project, respectively. The "Δ" column represents the average difference between those pre- and post-project ratings.* Numbers represent averages for the entire class. While roles were initially mapped to specific learning objectives and technical areas, data were not tallied separately for these students, since every student contributed to areas outside of their assigned role. The third survey element (Table 3) sought overall responses to the experience. The tabular surveys were followed by open-ended questions:

- What part of the project did you like the most?
- What part of the project was your least favorite? Did you have any general frustrations?
- In retrospect, would have you done anything differently between the time the project was assigned and the submission deadline?
- How could a project of this nature be improved?
- What other general comments come to mind?

Table 1. Learning Objectives Survey

On a scale of 1 to 5, note your level of comfort with the following learning objectives, where "1" means no comfort and "5" means high confidence. Responses are requested for all learning objectives, even those that did not relate directly to your project role(s).

Learning Objective	Pre	Post	Δ
1. Describe the role of biosignal conditioning/acquisition circuitry in a real context	2.4	3.6	1.3
2. Partition the design of a biomedical instrumentation system into smaller, more manageable tasks	2.6	4.1	1.4
3. Match team members to areas that maximize their interest and utilize their skills	3.2	3.8	0.6
4. Acquire physiological data with sensors	2.3	2.9	0.7
5. Condition biomedical signals to remove noise and other unwanted signal elements	2.7	3.5	0.8
6. Design programmable analog conditioning circuitry that can be controlled with digital sequences	1.9	3.6	1.7
7. Coordinate multi-channel signal acquisition and analog circuit programming with a central microcontroller	1.8	3.4	1.6
8. Complete the transition from schematic design to a fully populated PCB	2.4	3.5	1.1
9. Design & implement a LabVIEW virtual instrument to visual biomedical signals	1.5	2.8	1.4
10. Work more effectively with individuals having different areas of expertise	3.2	4.0	0.8
11. Document the features of a data acquisition system and instruct others in its use	3.0	3.9	0.9

Table 2. Technical Proficiency Survey

On a scale of 1 to 5, note your level of proficiency/understanding in the following areas, where a "1" denotes no proficiency and a "5" denotes a solid understanding of the concept.

Technical Area	Pre	Post	Δ
Biomedical sensor design and application	2.2	3.1	0.9
Instrumentation amplifier usage	3.4	4.4	1.1
Biosignal conditioning	2.8	3.5	0.7
Programmable filter design	1.9	3.6	1.7
Electrical isolation	2.5	3.5	1.0
Analog-to-digital conversion	3.1	3.9	0.8
Microcontroller programming	2.1	2.8	0.6
Task sequencing via a microcontroller	1.8	2.5	0.8
Creation of serial data streams	1.6	3.0	1.4
Serial communication protocols	1.8	3.3	1.5
Usage of an off-the-shelf USB module	1.4	3.4	1.9
Serial communication with a PC	1.7	3.1	1.4
User interface design in LabVIEW	1.6	3.3	1.7
Coordination of incoming data (to PC) versus outgoing commands (to board)	1.6	2.8	1.2
Board layout	2.2	2.9	0.8
Board fabrication	2.4	3.0	0.6

Table 3. Overall Experience Survey

Item	Val
Percentage of the board functionality that your team was able to successfully implement (1 = 20%, 2 = 40%, etc.)	4.1
Percentage of the PC functionality (user interface, PC-to-board interaction, etc.) that your team was able to successfully implement (1 = 20%, 2 = 40%, etc.)	3.6
Your personal level of interest in the material (1 = no interest, 5 = extreme interest)	4.3
Team effort required (1 = too little; 5 = too much)	3.9
Personal effort required (1 = too little; 5 = too much)	4.0
Access to instructor assistance (1 = nonexistent; 5 = ideal)	4.1
Staged deadlines & reviews (1 = no help; 5 = effective)	3.4
Hardware and software resources provided to enable the completion of your project (1 = inadequate; 5 = perfect)	3.4

D. Survey Interpretation

Learning Objectives Survey. After assessment of the formal written reports, it was clear that the project learning objectives were met. This is confirmed by the students' self assessments in Table 1. In every area, the students' perceived level of comfort increased between project onset and completion. The *most improvement* was noted on objectives 2, 6, 7, and 9, which address technical areas where the students were initially the least comfortable but required attention to realize a functional design. The nature of the project was a factor here, since system partitioning, programmable circuitry, microcontroller coordination, and the accompanying LabVIEW interface are the kinds of elements that only emerge in larger projects. Since a project this large is an atypical undergraduate experience, these areas offer more potential for learning. The *least improvement* was seen in objectives 3–5 and 10–11. One theme here relates to teaming with individuals with different areas of expertise, a familiar subject that offers students less learning potential. Objectives 4 and 5, which deal with biomedical signal acquisition and conditioning, received less emphasis because the students' time was primarily focused on getting the boards to work. A time extension would help in this regard.

Technical Proficiency Survey. As before, the technical areas that demonstrated the largest increase in perceived proficiency were those that were initially the least familiar to the students but required attention to achieve a working system: programmable analog filters, the USB module, and the LabVIEW interface. Serial data stream creation, the associated protocols, and serial communication with a PC were also technical areas associated with large proficiency increases. Biomedical sensors and signal conditioning again demonstrated small perceived increases, indicating that these areas need more emphasis in future project offerings. Finally, the areas of A/D conversions, microcontroller programming, and board layout/fabrication were associated with moderate proficiency gains. These areas were primarily owned by just one person per group, so the relatively low proficiency increases of the other team members in those areas would naturally lower the reported average.

Overall Experience Survey. This survey indicates that students were able to implement most of the planned board functionality and that they found the experience to be interesting. Students reported that the project required a lot of work, but that need was balanced by excellent access to instructor help. Lackluster responses to staged deadlines, design reviews, and hardware/software resources implies that these should be areas of focus in future offerings.

Open-Ended Questions. As in most survey instruments, the open-ended questions yielded the most interesting and useful data. When asked what they liked the most, the majority of the student responses (54.6%) identified specific technical areas: the LabVIEW interface, serial data communication, microcontroller programming, analog circuit design, and PCB layout/fabrication. On a related note, 21% of the responses mentioned the freedom offered by the open-ended nature of the analog circuitry and stated their interest in innovative circuits presented by fellow students. Many positive responses (37.8%) pointed to high-level project aspects: the cross-course effort itself, the hands-on opportunity, and the ability to mold ideas into a functional, complex, and integrated product; an opportunity that can be difficult to offer in a fast-paced undergraduate curriculum.

When asked what they liked the least, student responses varied. One thematic grouping (50.4%) related to LabVIEW: its learning curve, serial communications between LabVIEW and the board, and the feeling that LabVIEW developers were separated from the rest of the group because the hardware issues were outside their sphere of influence. Some responses (20.8%) dealt with poor team communication, awkward team dynamics, and difficulty coordinating schedules. The instructors found these responses encouraging, as the project clearly exposed students to issues that are hard to address in college but are faced everyday by practicing engineers. Remaining survey responses (8.4%) addressed expected items such as a lack of time in a busy semester and specific technical difficulties.

When considering what they would do differently, students provided responses that dealt primarily with non-technical issues, e.g., team dynamics (43%) and time management (17.2%). The former included more careful project assignments, more proactive responses to needs of struggling teammates, better communication to meet deadlines, and more frequent interactions with instructors. The latter theme recognizes the belated desire to start programming, construction, and testing processes earlier to leave time for unavoidable design iterations. To their credit, four students (17.4% of responses) stated they would not have done anything differently during the semester.

Students suggested a number of project improvements. As expected, 36.7% of the responses pointed to a decrease in project scope (less functionality, a portion of the system, etc.) or more project completion time. One block of responses (36.7%) addressed the need for increased resource access and a more tightly coupled relationship between the project and earlier learning experiences. This block included relating the project more closely to earlier EECE 628 exercises, a desire for more direction (which opposes the desire for open-ended experiences), multiple-group design reviews that would help groups learn from one another, and better access to technical resources (e.g., reference designs for programmable filters or the USB daughter card). A small number of comments (13.2%) focused on the need for PCB layout instruction, time allotments for microcontroller and LabVIEW learning curves, and more flexibility in the choice of microcontroller and visualization interface.

A fair portion (42%) of the students' general comments praised the effort as a good final project that was enjoyable, interesting, and industry-like in its implementation. Some were grateful to engage in the project as preparation for full-time employment, and they liked tackling unforeseen complications that offered interesting design tradeoffs. While the project was admittedly overwhelming to some students, they found satisfaction in the completion of a complex design and relied on team members. Some responses (25.2%) touted the benefits of these group experiences, noting the challenges posed to their social skills. A recurring theme was that products produced by these students would be excellent references or starting points for future efforts, allowing students to more fully test and debug small pieces of a system without the need to wait until the end of the semester to pull the different facets of the system together.

E. General Lessons Learned

The overall student response to this effort was highly enthusiastic. Students found satisfaction in completing an integrated system, and they benefited from the community dynamics nurtured by other students and the faculty mentors. The aggregate experience was refreshing compared to normal course work, and students demonstrated ownership in project areas that required discovery. The instructors were reminded that it can be beneficial to assign two students per task at this developmental stage. Some students must address multiple tasks; subject areas overlap, and predicting the relative work per task can be difficult. In any development environment, more experienced individuals may need to step in and aid their teammates for the sake of successful and timely project completion.

This project was arguably too large for the time allotted, though the students' work ethics pushed their boards to a first stage of completion. It would make an excellent two-semester endeavor, where the first semester would focus on a literature search, a market survey, a project plan, ramp-up time for students exposed to new design areas, and the construction of an early prototype. The second semester could then focus on design iterations, packaging, and the presentation/report for the final product.

V. CONCLUSION

This paper presented a cross-course design project that merged emphasis areas from a bioinstrumentation course with data acquisition and communication topics from a generic electronic instrumentation course. The goal was to create a more substantive design experience in an application area with clear societal benefit. Given informal student feedback, data from post-course surveys, the quality of the final reports, and the products produced by the student groups, the instructors consider this effort a successful learning experience and plan to improve the project in future semesters. While this team design effort required more work than a typical undergraduate project, students stated an appreciation for integrated efforts that require discovery, promote teamwork, and result in tangible products.

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