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Senior Design in the Setting of Multidisciplinary Research*

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Multidisciplinary research projects in biomedical engineering (BME) may require undergraduate students to perform in areas where they have limited exposure or on tasks that challenge their emergent engineering skills. However, an undergraduate's inexperience can be offset and the likelihood of project success can be improved with careful selection of faculty and graduate student preceptors. Unfortunately, overtaxed faculty mentors, especially in today's competitive medical and academic centres, often are inaccessible or reluctant to mentor if time commitments and outcomes are uncertain. Thus, we proactively restructured the typical mentoring hierarchy in a top-down manner by pooling two bioengineering faculty, a clinician scientist and a senior graduate student to mentor one undergraduate. Our approach generated a project that fulfilled educational and research objectives. Participants reported satisfaction with project outcomes, their role in the process and the mentoring paradigm employed. We believe that alternative mentoring models for multidisciplinary BME research projects should be employed when establishing senior design experiences and that superior results are achieved when equal weights of effort are expended in defining the composition of the mentoring team as well as in defining the project itself.

Keywords: Capstone; mentor(ing); multidisciplinary; biomedical engineering

INTRODUCTION

FOR A UNIVERSITY ENGINEERING FACULTY, the task of arranging, mentoring and supervising student project work, either for novice engineering undergraduates encountering their first project assignment or for intermediate engineering graduate students assuming their first advisory roles, is complex. Clearly, the intricacies of project selection, supervision and execution are multifactorial and periodic review and revision of the process is justified. Likewise, review of the mentoring model used is essential, in part, due to the many new challenges confronting faculty in higher education. Modern academic research centres unintentionally force faculty to choose between teaching and research. Faculties choosing to teach are drifting further away from mainstream, topical research areas and are finding that they are unable to offer diverse project options for their students or the resources necessary to support them. Faculties choosing to focus on their research are increasingly separated from students willing to undertake project work on a short-term basis and are challenged to allocate sufficient time resources for the hands-on supervision of those who perform project work in the laboratory. This situation is further exacerbated in busy teaching and research medical facilities where biomedical scientists and engineers seek to interface with their clinical counterparts. Thus, the competing demands of the teaching, research and clinical faculties may lead to projects that are marginally associated with state-of-the-art research endeavours, inadequate to motivate the most creative efforts of either faculty or student, beyond the capabilities of the novice engineer, not inspirational to graduate students involved in project development or management, deficient in comprehensive instructional qualities and, generally, unsatisfactory to everyone involved.

Interestingly, most agree with the essential elements in successful project work as outlined by the ABET criteria [1] and senior design workshops [2] and in attempts by engineering faculty to define design coursework and projects in multidisciplinary [3] and biomedical [4] settings. Additional, albeit unofficial, tenets (T1–T5) related to the specific academic and research goals of biomedical engineering as practiced by some of our faculty in the Joint Department of Biomedical Engineering at the University of North Carolina and North Carolina State University (JBME) are listed below:

T1. Successful projects not only lead to useful deliverables, but also lead to deliverables that are used
T2. Successful project work is translational and produces a smooth transition from theory to practice
T3. Successful project work incorporates both previous and current coursework and reinforces the interdependence of each

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T4. Successful project work exploits the strengths of the students and faculty involved and provides adequate opportunities for students to learn new skills

T5. Successful project work, finally, is seen as a mutually beneficial effort for all parties involved and may span the fields of research, medicine, business and academia.

If we honestly assess how we organize and perform project work, we must acknowledge that the following scenario is not at all unusual. The undergraduate preceptor assembles small groups of undergraduate students for project work while the graduate preceptor undertakes a similar effort with graduate students seeking mentoring experiences. Both make requests to the faculty for project mentors and candidate projects. The response from the faculty may be inadequate and personal solicitations follow. Overall, the traditional structure of the developing mentoring relationship is that of a pyramid: one faculty mentor at the apex, one or two graduate students from the mentor's laboratory in the middle and a base composed of several undergraduate students ostensibly working as a team on one project or independently working on a group of interrelated projects. Assembled projects from the teaching faculty, while tightly coupled to the curriculum and replete with suitable instructional infrastructure, may be routine or only moderately challenging. In contrast, projects proposed by the research and medical faculty may pose an excessive challenge to the undergraduate student and may lack both a clear connection to the curriculum as well as a defined instructional organization.

Undergraduate students may experience frustration with too much or too little challenge and inadequate mentor accessibility, faculty may become exasperated with a lack of progress and failures in the development of a useful deliverable, less assertive undergraduate students may not get the opportunity to develop independent leadership skills and graduate students may become uncomfortable in their new-found instructional role since they, too, are not receiving the direction they need with their unfamiliar responsibilities. Likewise, if we are equally honest in assessing our selection criteria for mentors and mentoring teams related to project work, we must reluctantly acknowledge that we are much more likely to be *reactive* than *proactive*. Thus, mentoring team decisions often are based on who has the time, the resources and the expressed interest in mentoring a student rather than devoting the substantial effort necessary to recruit and assemble a team that would best serve the student's academic programme in light of the mentor's research goals and project proposal.

In this manuscript, we report on our experience in turning the traditional project design pyramid upside-down, thereby challenging the suitability of the structure in the setting of a multidisciplinary research environment (e.g. biomedical engineering). The model we established was heavy on mentors and light on students. Each participating faculty mentor was selected to contribute specific research and instructional components to the project design and implementation and both of the students involved had clearly defined roles and responsibilities. Lines of communication between the individuals within that structure were obvious and sufficient opportunities to interact as well as instruct were conferred by the design. In the final analysis, the project work led to a satisfactory deliverable to the research faculty, a valuable instructional tool for the teaching faculty and documented accomplishments for the students involved. Finally, anticipating that our experiences were not unique, we surveyed our faculty to document similar mentoring trends, the composition of mentoring teams, project outcomes and the overall degree of satisfaction with co-mentoring experiences.

Project team

For our project, we assembled a five-member team of mentoring faculty (an engineering instrumentation research specialist, an engineering signal processing expert, a practicing clinician with a definitive research agenda), a graduate student with four years of research and academic credentials and a senior applied science student embarking on a senior design research project during a final year of undergraduate study. The clinician-scientist and lead core faculty member in BME had an established research-based collaboration that integrated biomedical signal collection and processing in clinical and experimental settings. When approached by an undergraduate student expressing interests in signal processing, instrumentation and translational research as senior design project work, both faculty members suggested the development of a second generation, more generalized version of the current signal acquisition tool. However, three obstacles were immediately apparent: one, the physician had growing clinical responsibilities that were limiting his ability to address existing research agendas, thereby leaving little time for new efforts; two, the BME faculty member had similar non-clinical commitments that would limit supervisory obligations and exclude a sole mentorship role; and three, initiatives to expand signal processing would require the collaboration of an unidentified expert in the field. In response to those limitations, the faculty first enlisted the collaboration of an advanced graduate student to oversee daily project management and provide the required time commitments necessary to achieve project goals. The selection of that student was made on the basis of the student's status within the BME graduate programme, the student's need to fulfill teaching and mentoring requirements of a PhD programme using this mechanism and, finally, the student's demonstrated expertise in digital signal analysis techniques as well as an expert knowledge using the selected programming language

(LabVIEW^{TM}). Finally, after an initial planning meeting to discuss general project components, it was decided that a third BME faculty member needed to be recruited in order to solidify and expand digital processing protocols. While that faculty member was selected principally for signal processing expertise, an added benefit was the familiarity of that individual with the undergraduate curriculum and the undergraduate student's achievements and previous coursework in the programme.

Once selected, the entire team met to outline general roles and responsibilities and an initial time-line was established for the completion of the project which eventually spanned 18 months. Thereafter, communication and interactions between team members were facilitated with face-to-face meetings, web-conferences and electronic postings and updates. In general, the faculty established the project boundaries and objectives while the graduate student implemented the plan and interacted with the undergraduate student responsible for executing it. From the outset, the team defined overall goals and expectations so that participants were able to understand their unique contribution to the project as well as appreciate specific benefits by making that commitment to participate. The general roles, responsibilities and modes of interaction between the collaborating parties are outlined in Table 1.

Project description

As noted above, the clinical research faculty member had previously identified a need for a comprehensive analogue signal acquisition and power spectral processing program. Preliminary work [5] demonstrated the scientific value of the spectral information from the electrocardiogram collected during ventricular fibrillation (VF) in the heart. Specifically, it was shown that the median frequency of the electrocardiogram fell during the initial few minutes of ischaemic VF by about 50%. Partial to complete restoration of coronary flow before defibrillation manoeuvres restored much of the median frequency content of the signals. Interestingly, the minimum defibrillation energy necessary to re-establish a normal sinus rhythm was less during a partial restoration of blood flow in the coronary artery when compared to the energy necessary following a complete restoration of coronary flow. Collectively, the team suggested several innovative ways to understand the root cause of that observation, but the original data processing and display system lacked the required features and capabilities necessary to interrogate the data with those objectives in mind. Thus, the basic research and engineering faculty joined with the clinician and defined the scope of the project which included a comprehensive and flexible state-of-the-art data acquisition platform, a multifunctional data selection and analysis capability, data display features that included the most common power spectral analysis tools and, finally, simple software tools to permit verification of system performance and accuracy while allowing users to generate simple test signal constructs and explore processing outcomes using those known inputs.

Project implementation

The program we developed (**PAAS**, **P**rogram to **A**cquire and **A**nalyze **S**ignals) features real-time signal acquisition, along with analysis and test signal generation written in LabVIEW^{TM} (LV) for use with National Instruments^{TM} (NI) hardware. Our intent was to duplicate and upgrade the capabilities of our existing collection and analysis software while generalizing the routines and expanding its capabilities to include additional time- and frequency-domain analyses. Separate panels for each feature of the new program allow different aspects to be operated independently. In its final form, the program has four panels: a data acquisition panel, two signal selection and analysis panels and a signal generation and data conversion panel. A brief description of the project follows and an executable version of this program, along with a simple *User Manual*, which is available from the authors using the electronic contact information provided through a no-cost end-user licence agreement drafted by The University of North Carolina at Chapel Hill.

In the signal acquisition panel (Fig. 1), data collection parameters are designed to be user selectable. The voltage range, A/D conversion bits, number of channels and sample rate are designed to be altered in accordance with the NI hardware used. Three waveform graphs are employed to simultaneously display separate channels of analogue data selected by the user. As the signals are collected, data are stored in 16-bit binary format. Signal collection can be paused and resumed without changing data collection files or collection protocols. A log of events registered to particular data segments may be generated by the user in real-time and saved in a separate ASCII file. A status display is included on this panel which shows the disk volume label and the size of the current data file. This portion of PAAS is essentially a re-implementation of the original programming, except the platform was upgraded to a much later version of LabVIEW$^{ⓉⓂ}$ and default values implemented (sample rate, time-stamped file names, channels collected and displayed, etc.) so that untrained technicians could, in three mouse clicks, safely initiate and store relevant data in either laboratory or clinical settings.

Additionally, two panels were designed for off-line signal analysis following real-time acquisition, using a previously collected and stored signal or using a digitally generated and stored test signals. The first analysis panel (Fig. 2) was designed to enable the user to select a data file and load an initial portion of that file. For long data records, it is possible for the user to load only a portion of the total data record (*e.g.,* 0–10 min) in order to avoid

Table 1. Roles, areas of experience and expertise and interactions of project partipants. Bracketed number beneath each participant's initials indicates that individual's entry into the mentoring paradigm

Project participant	Role in project	Specific areas of expertise and relevant experiences	Faculty-to-faculty, faculty-to-student and student-to-student contact time and approach
TAJ [2]	*Overall project director and biomedical engineering faculty preceptor.* • Recruited project participants and led in the definition of project objectives. • Collaborated with other preceptors in establishing project milestones. • Provided expertise in instrumentation interface and design. • Evaluated final project outcomes in light of defined objectives.	• Broad experience in real-time data acquisition, processing and display. • Previously partnered with the clinical faculty preceptor in the initial animal experimentation that confirmed the behaviour and significance of ECG power spectra during fibrillation. • Experience with power spectral analysis techniques in the clinical setting.	Weekly meetings between TAJ and the undergraduate and graduate student for project updates and problem resolution. Typical meeting times were 1–1.5 hours. After TAJ's relocation to ECU in the final months of the project period, meetings with the students and the other BME faculty occurred on a twice-monthly basis via videoconference as well as monthly on-site, half-day meetings at both UNC and ECU.
RTC [4]	*Graduate student liaison between faculty preceptors and the undergraduate student.* • Coordinated programming efforts and provided oversight to the undergraduate student's work. • Assisted in hardware and software validation. • Established program and user manual dissemination platform.	• Expertise in LabVIEW$^{\text{TM}}$ code generation and digital signal collection, processing and display. • Experience in translating the more complex project components to defined sub-tasks easily understood and implemented by the less experienced undergraduate student.	RTC and JWH met three–four times weekly for 1 hour. Meetings were arranged to test newly added software components, confirm collection, display and analysis sub-routines, integrate new programming code into existing structures, summarize current literature reports relevant to the project, test hardware configurations and develop test models for the system. At RTC's request, mentoring faculty frequently were invited to join the meeting and contribute specific instruction and design critique.
JWH [3]	*Undergraduate student engaged in project work.* • Generated the program code. • Assisted in program validation studies. • Compiled and edited introductory user manual.	• Fundamental skill set in programming, signal collection, data processing, instrumentation and control. • Established relationship with the BME faculty preceptors and a familiarity with the clinical faculty preceptor's work.	
SRQ [5]	*Biomedical engineering faculty preceptor and Associate Chair of the undergraduate program in Applied Science at UNC.* • Defined DSP components for use in the project. • Director the students in the application of DSP components. • Assisted in the validation of the final project.	• Extensive experience in digital signal processing, display and interpretation. • Thorough knowledge of the undergraduate curriculum and the undergraduate student's preparatory status. • Experience in providing links between different elements of this project and the undergraduate curricular experiences of the student.	Semi-monthly meetings between SRQ and the undergraduate and graduate students and faculty project director. These meetings typically lasted 1–1.5 hours and were held in the instrumentation laboratory where the hardware/software interfaces were being developed.
CWB [1]	*Clinical faculty preceptor.* • Provided clinical and experimental motivation for pursuing this project work. • Assisted in defining the elements of the program and establishing realistic operational constraints for use in the clinical setting. • Evaluated the final program and established its equivalence with prior collection and processing methodologies.	• Experienced in LabVIEW$^{\text{TM}}$ code generation and application, basic and clinical research design, and the experimental limitations/ considerations in the clinical environment. • Principal architect of the utility of the ECG power spectra in identifying underlying pathophysiology in the clinical setting at UNC as well as documenting those findings in controlled animal experimentation.	After initial face-to-face meetings with all parties involved at UNC, CWB's subsequent interactions with the undergraduate and graduate students and faculty cohorts were electronically facilitated by email and SharePoint® postings due to a relocation to UCSF during the latter part of the project.

exhausting available system RAM. The selected portion of the data record may be plotted, along with event markers, and previewed using one minute data segments. A second plot of the data enables cursor selection of a region of interest within a data record. Once selected, the region of interest is segmented into user defined time epochs (based on a power-of-two number of data points to facilitate FFT and power analyses) and time, power and spectral analyses are performed on each epoch of the data. Several types of analyses are generated, including the power spectrum, auto- and cross-correlation, auto- and cross-spectra and coherence. Power spectrum results are presented for individual segments on the first signal analysis panel. All other analyses are averaged across time

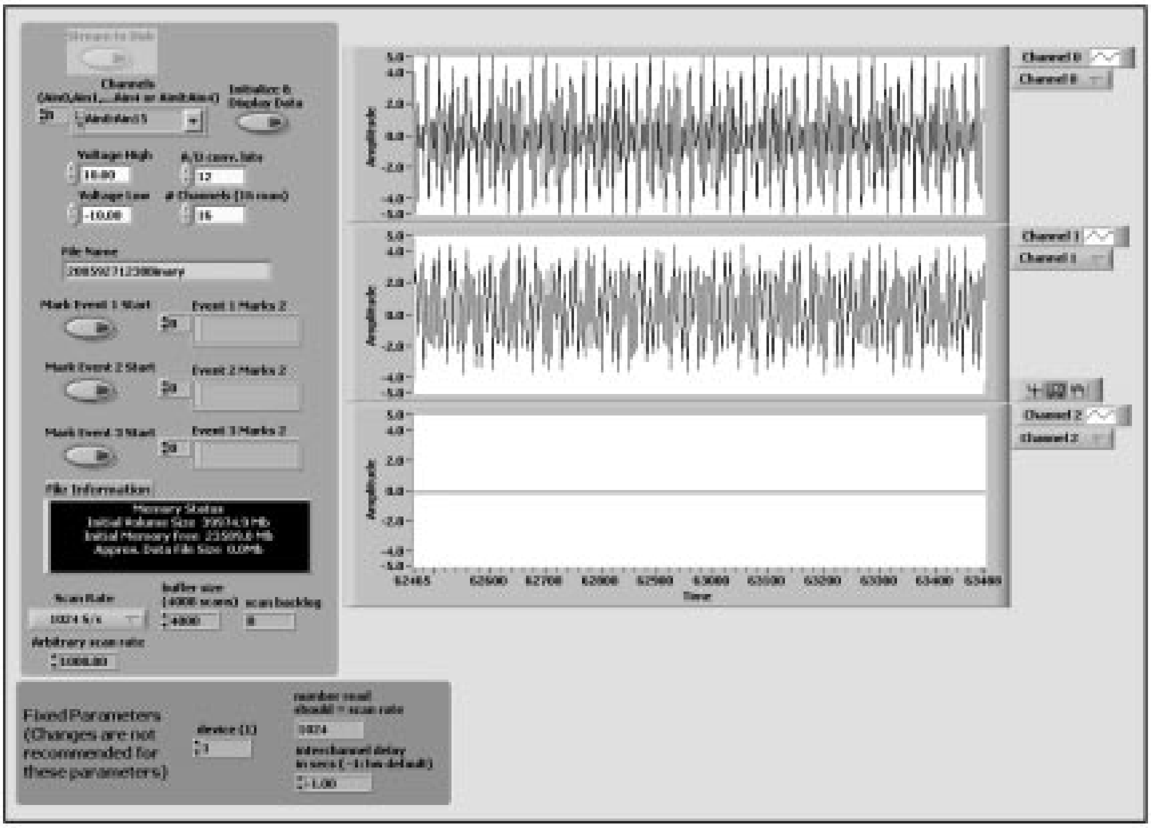


Fig. 1. **LV data collection panel**. Up to three waveform charts are employed for display of the data collected using NI DAQ hardware. User selectable signal acquisition parameters are shown on the left along with event markers. The signals shown in the upper two plots are the two test signals sampled at 1024 S/sec. Source: PAAS©2006, R. T. Cole, J. W. Hutchinson, C. W. Barton, S. R. Quint, and T. A. Johnson.

epochs and are accessible on the second analysis panel (Fig. 3). Results from all analyses may be exported to a spreadsheet file for further inspection, statistical assessment and summary display using other processing platforms (*e.g.* EXCEL, SPSS, MATLAB).

Finally, a fourth panel in the program (Fig. 4.) was designed for the generation of user-defined test data. A one minute segment for two signals may be generated and placed in an external data file. Each signal is formed by the summation of as many as four sinusoids having known amplitudes, frequencies, phases and sample rates. Once generated, the signals are written to a data file. That file, in turn, can be reloaded using the signal analysis panels and processed as though it were source data collected from the ADC. The data generator panel also enables conversion of text-formatted data files into a suitable binary format for import into the data analysis panels, thereby allowing a wider range of signal sources to be analyzed.

Verification and instructional examples

As noted previously, our team believes that instructional and verification components are essential for meaningful project work. Thus, we incorporated those features into this project design. In the sections that follow, we first outline simple verification examples of the code. We then present two uses of the program for instructional purposes. Thus, via the signal generation panel, we allow students to evaluate as well as manipulate test signals while they struggle to comprehend power spectral analysis.

Two input signals were generated, collected and analyzed to illustrate the typical functioning of the code as well as the form and interpretation of assembled outputs. The two test signals were produced using the data generation feature of this program. Signals were constructed using the selected frequency components and phase shifts. The two signals were generated and stored on two separate occasions using different sample rates, 1024 and 2048 S/sec (samples/second). The formula used to generate test signals is given below, where n = sample point and T = sample period (either 1/1024 sec/S or 1/2048 sec/S). Note the phase shifts introduced and the absence of a second term in Equation (2).

$$\begin{aligned}\text{Signal}_1 &= \sin(200\pi nT) + 2\sin(400\pi nT)\\ &\quad + 3\sin(600\pi nT) + \sin(1200\pi nT) \qquad (1)\end{aligned}$$

$$\begin{aligned}\text{Signal}_2 &= \sin\left(200\pi nT - \frac{\pi}{2}\right) + 0\\ &\quad + 3\sin\left(600\pi nT + \frac{\pi}{2}\right) + \sin(1200\pi nT) \qquad (2)\end{aligned}$$

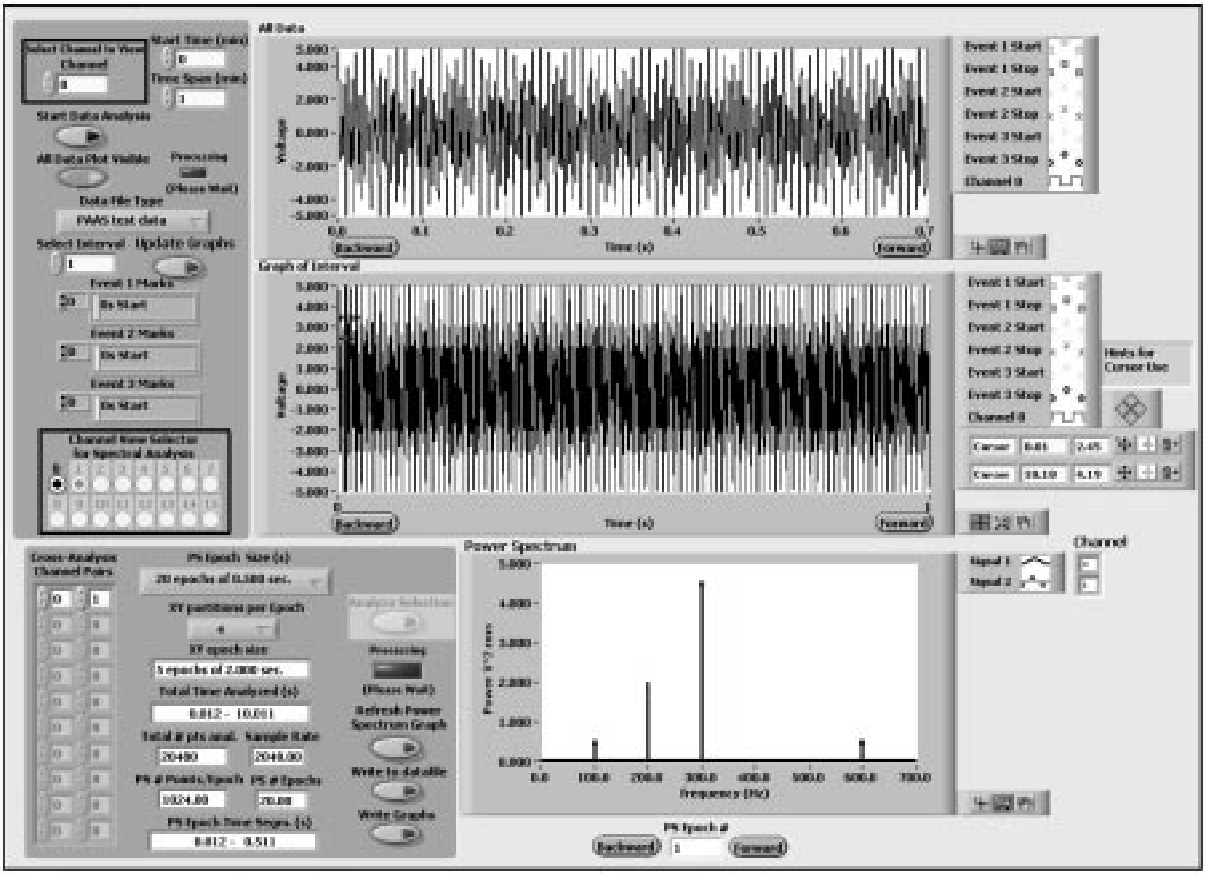


Fig. 2. **LV data analysis panel 1**. All channels of the data file are read in on this panel and can be displayed, one channel at a time, in the upper graph. Data in the upper graph is decimated (every other point in the display only) to reduce memory requirements. The middle graph displays a portion of the full, undecimated data and allows cursor selection of an analysis region. The signal shown in the upper two plots was generated at 2048 S/sec. Controls for customizing analysis display, for cross-analysis choices, and for time epoch selections appear on the left. The Power Spectrum of both test signals is illustrated in the lower plot. Selected channels (two in this case) are overlaid in this plot using a solid line for Signal$_1$ and connected boxes for Signal$_2$. Though in grayscale for the manuscript figures, PAAS employs color distinctions for each channel's analyses outputs. PAAS©2006, R. T. Cole, J. W. Hutchinson, C. W. Barton, S. R. Quint, and T. A. Johnson.

Figure 1 illustrates the program's data collection capabilities by showing the collection of the two test signals sampled at 1024 S/sec. Data generated for Signal$_1$ at the higher sampling interval (2048 S/s) is shown in Fig. 2. Note that PAAS loads data from both signals, but only a single signal can be displayed on the analysis graph at a time. The power spectrum of the test signals should produce single peaks of proper amplitude at each of the component frequencies (100, 200 300 and 600 Hz for Signal$_1$ and 100, 300 and 600 Hz for Signal$_2$). The power spectrum, in the lower plot of Fig. 2, shows those peaks. The amplitudes of the peaks are 0.5, 2.0, 4.5 and 0.5 for Signal$_1$ and 0.5, 0, 4.5 and 0.5 for Signal$_2$ at 100, 200, 300 and 600 Hz, respectively. Zero amplitude for the second peak in Signal$_2$ is due to the absence of the 200 Hz frequency component.

As background for verification of the power spectra observed in Fig. 2, recall that the compact Fourier Series representation of a periodic signal is given in Equation 3 [6].

$$x(t) = \sum_{k=-\infty}^{\infty} A_k e^{j2\pi f_k t}$$

$$\text{where} \quad A_k = |A_k| e^{-j\theta_k} \qquad k = \pm 1, \pm 2, \pm 3, \ldots$$

$$\text{and} \quad |A_k| = \frac{1}{2}\sqrt{a_k^2 + b_k^2} \tag{3}$$

The auto-power spectra and auto-spectra are identical processes and are defined as the sum of the magnitude of the Fast Fourier Transform (FFT) at each frequency, where, for one-sided spectra, the amplitude is doubled, except for the dc value[7][8]. Since the amplitude of the input signals for each frequency component are 1, 2, 3 and 1 for Signal$_1$ and 1, 0, 3 and 1 for Signal$_2$, respectively, the amplitudes at each frequency are as expected. For example, from Equation 3, the magnitude squared of the signal with an amplitude of 3 would be $(3/2)^2$ or 2.25. Doubling this value produces a magnitude of 4.5 as shown in the

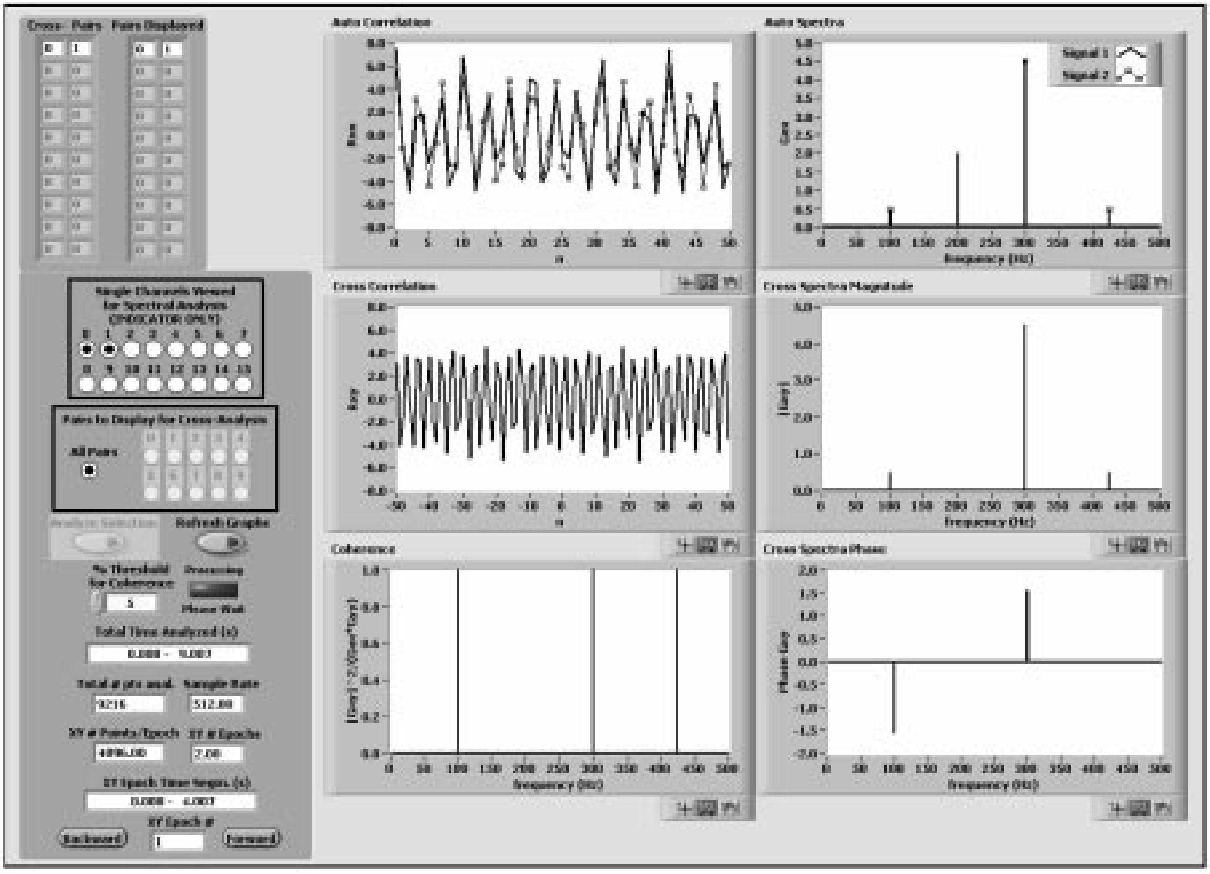


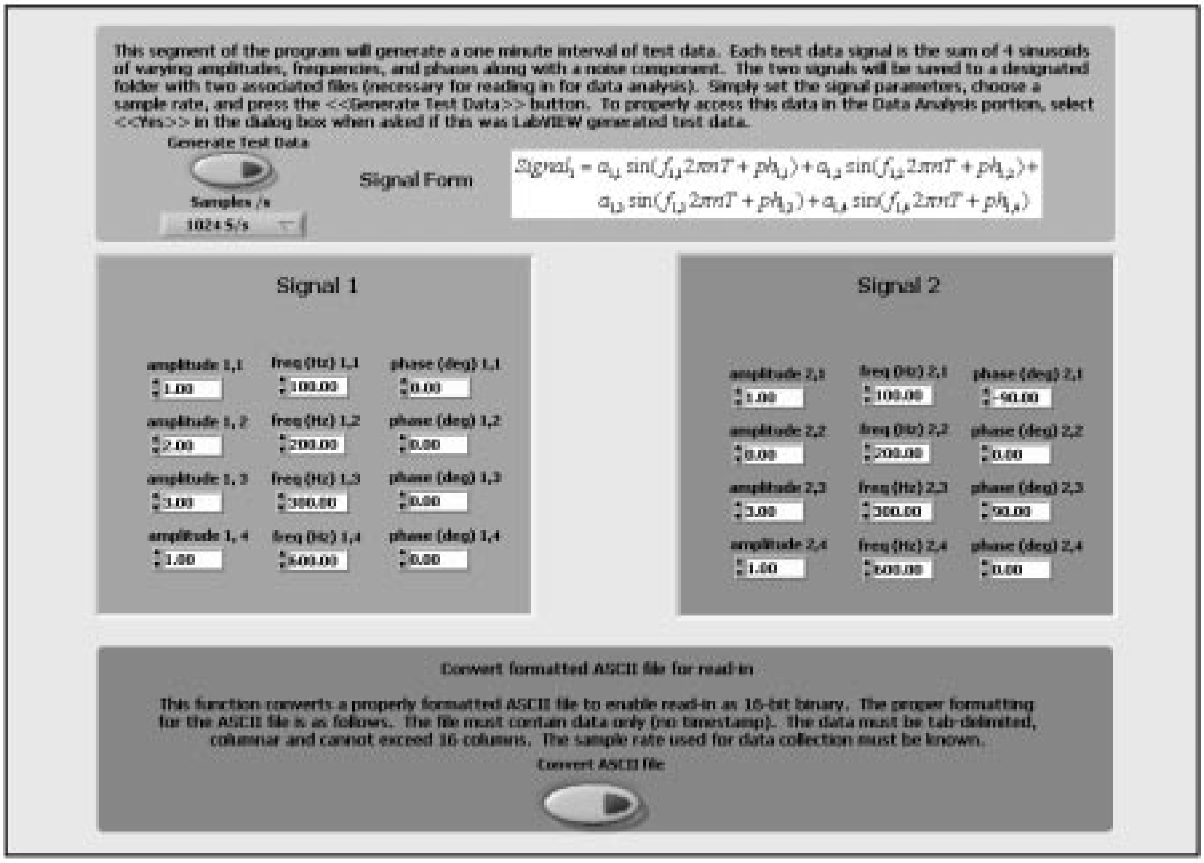
Fig. 3. **LV data analysis panel 2**. Additional analysis graphs are presented on the second analysis panel. These include auto- and cross-correlation (upper and middle plots on left), auto- and cross-spectra (plots on right), and coherence (lower plot on left). Controls and information regarding channel views, cross-analysis pairs and time epoch selections are displayed on the left. Different line types (solid and connected point) are used for the auto-correlation and auto-spectral plots, however, only a solid line was required for the cross analysis plots. Signals analyzed were those generated at 1024 S/sec. Though in grayscale for the manuscript figures, PAAS employs color distinctions for each channel's analyses outputs. Source: PAAS©2006, R. T. Cole, J. W. Hutchinson, C. W. Barton, S. R. Quint, and T. A. Johnson.

results plot for the 300 Hz signal. The cross-spectra magnitudes at 100, 200, 300, and 600 Hz are 0.5, 0, 4.5 and 0.5, respectively. As before, the absence of the 200 Hz term in Signal$_2$ is responsible for the zero magnitude at that frequency. Similarly, coherence at 100, 300 and 600 Hz is 1.0 and zero at 200 Hz. Finally, the cross-spectra phase plots show a -1.5 rad phase shift at 100 Hz and a $+1.5$ rad shift at 300 Hz which are consistent with phase shifts introduced into the test signals.

As a further example of the verification and instructional capabilities, examination of the same analysis at a generation rate of 1024 S/sec (Fig. 3) yields insight into sample theory and aliasing. For all intents and purposes, the results are identical to those produced at 2048 S/sec, except the 600 Hz frequency band has been shifted to 424 Hz. Both signals were generated at 1024 S/s. This is greater than the Nyquist frequency for the 100, 200 and 300 Hz components of the signals, but less than the Nyquist frequency for the 600 Hz component. Since the 600 Hz portion of the signal was undersampled by 176 S/s, there is a single peak at (600–176) Hz, (or 424 Hz) with the appropriate amplitude [6].

Project assessment

Our thesis in this report is that the traditional structure of a senior research project may not always be the best structure, especially in multidisciplinary environments. We propose that the structure adopted for any particular project must produce deliverables, provide a smooth transition from theory to practice, incorporate past and current coursework, provide a platform for the acquisition of new skills and, finally, benefit everyone involved. Further, we propose that instances can be found where greater participation and more satisfactory results can be achieved using a modified project structure, especially when the changing landscape of current research and educational institutions is considered. Clearly, the inverted structure we used (several mentors interfacing with a single undergraduate student through a single graduate student co-mentor *versus* a single faculty mentor interfacing with several undergraduates through one or more graduate student co-mentors) is an extreme example of modified project architecture. However, we believe that the success of our inverse paradigm demonstrates that any structure between those two extremes has



This segment of the program will generate a one minute interval of test data. Each test data signal is the sum of 4 sinusoids of varying amplitudes, frequencies, and phases along with a noise component. The two signals will be saved to a designated folder with two associated files (necessary for reading in for data analysis). Simply set the signal parameters, choose a sample rate, and press the <<Generate Test Data>> button. To properly access this data in the Data Analysis portion, select <<Yes>> in the dialog box when asked if this was LabVIEW generated test data.

Signal Form

$$Signal_1 = a_{1,1}\sin(f_{1,1}2\pi nT + ph_{1,1}) + a_{1,2}\sin(f_{1,2}2\pi nT + ph_{1,2}) + a_{1,3}\sin(f_{1,3}2\pi nT + ph_{1,3}) + a_{1,4}\sin(f_{1,4}2\pi nT + ph_{1,4})$$

Samples /s
1024 S/s

Signal 1

amplitude 1,1 1.00	freq (Hz) 1,1 100.00	phase (deg) 1,1 0.00
amplitude 1, 2 2.00	freq (Hz) 1,2 200.00	phase (deg) 1,2 0.00
amplitude 1, 3 3.00	freq (Hz) 1,3 300.00	phase (deg) 1,3 0.00
amplitude 1, 4 1.00	freq (Hz) 1,4 600.00	phase (deg) 1,4 0.00

Signal 2

amplitude 2,1 1.00	freq (Hz) 2,1 100.00	phase (deg) 2,1 -90.00
amplitude 2,2 0.00	freq (Hz) 2,2 200.00	phase (deg) 2,2 0.00
amplitude 2,3 3.00	freq (Hz) 2,3 300.00	phase (deg) 2,3 90.00
amplitude 2,4 1.00	freq (Hz) 2,4 600.00	phase (deg) 2,4 0.00

Convert formatted ASCII file for read-in

This function converts a properly formatted ASCII file to enable read-in as 16-bit binary. The proper formatting for the ASCII file is as follows. The file must contain data only (no timestamp). The data must be tab-delimited, columnar and cannot exceed 16 columns. The sample rate used for data collection must be known.

Fig. 4. **LV data generation panel**. In this panel, two alternate forms of data entry into the main analysis panels are provided. In one pathway, two separate data signals can be generated using a summation of known sine wave components that are subsequently sampled and saved for retrieval by the analysis panels. In the second pathway, ASCII formatted data collected from other sources can be imported for analysis. PAAS©2006, R. T. Cole, J. W. Hutchinson, C. W. Barton, S. R. Quint, and T. A. Johnson.

potential benefit and utility and that those potentials need to be exploited on a project-by-project basis. Student-faculty interactions with the development of the specific components of PAAS should be evident with a review of the PAAS program and Table 1 as outlined above. Specifically, it should be clear that the impetus for the project arose from the clinician scientist who, in turn, collaborated with an instrument design specialist and both students in the generation of the data collection panel (Panel 1). As the project matured, a DSP specialist interfaced with the students and other faculty to significantly expand signal analysis capabilities (Panels 2 and 3). Finally, owing to the instructional and verification components of the project, it should be obvious from the examples presented how the two BME faculty and the students jointly defined the fourth panel of PAAS and envisaged its use for instruction and verification.

Thus, we believe we have demonstrated that the undergraduate research project presented above produced a significant deliverable that is both useful and used. The program, the instrumentation, the signal processing algorithms and the presentation of the analyses incorporated state-of-the-art features of programming techniques, digital signal processing theory and practice, instrumentation, graphic user interface and, importantly, test, validation and instructional utilities. In addition, it was clear to us that faculty involvement and participation was maximized and facilitated by this structure. While a strong argument can be made that our adopted structure simply distributed faculty responsibilities on a single project rather than the amplified responsibility of just one faculty advisor via the traditional mentoring paradigm, an equally compelling argument can be made that our structure increased participation by faculty that would have otherwise been reluctant to engage in a project where sole responsibility was expected. Specifically, the participation of a clinician as part of the mentoring faculty in this project could have been achieved only under the structure employed and the lack of his participation would have diminished the relevance of the project and its successful outcome. Thus, we affirm that faculty participation increased, the structure provided suitable faculty rewards [9] and collective faculty responsibilities [10] were realized.

At the present time, PAAS is being evaluated for use in three different experimental and clinical settings. At the University of California—San

Francisco, PAAS is being evaluated in order to assess its utility as a replacement for the original program. At East Carolina University, PAAS is being used for the experimental interrogation of cell-to-cell calcium transients in cultured stem cells where the goal is to verify and quantify the development of cell communication via gap junctions as cells mature. Finally, also at ECU, PAAS is being used to collect high-fidelity proximal and distal coronary artery pressure recordings across vessel lesions in the clinical cardiac catheterization laboratories at the time of stenting with the goal of establishing a more rigorous quantification of lesion haemodynamics and define better therapeutic strategies. As noted previously, a no-cost licence is available for PAAS from the authors and we expect that other groups will similarly find it valuable as an investigative tool.

Finally, we must consider the benefit to the students involved. For the graduate student, a unique opportunity to lead as well as instruct was provided in this structure. The graduate student also had an opportunity to assume a leadership role under the tutelage of experienced faculty and develop a unique mentoring style. Both are expected by the curriculum to be demonstrated and documented in preparation for graduate school PhD candidacy. Likewise, the undergraduate student was entrusted with project responsibilities that could not be deferred to other students and, therefore, developed leadership and research skills as well. In addition to the deliverable PAAS, the undergraduate student provided other evidence of successful project outcomes. Specifically, the undergraduate student was able to present this project work at several local and national meetings [11][12], leveraged it to secure external funding (see acknowledgement), saw it lead to a university report of invention and, now, a published report, all of which will be used to document his preparedness for advanced graduate study in biomedical engineering or continued employment in biomedical research. While the undergraduate student did not get a genuine 'team' experience with students on a similar academic level, we believe that ample opportunities for those experiences are provided by other activities in the engineering curriculum and that the benefits of developing independent project skills far outweigh the loss of that singular experience in project work.

Student assessment

During the preparation of this manuscript, the undergraduate and graduate student participants, both of whom are co-authors of this work, submitted specific comments and critiques to be included as part of the manuscript:

Undergraduate perspective

A heavily mentored project was the type of experience I was seeking. With this type of project, I was able to draw on the experiences and expertise of several professors instead of only one. Additionally, I could work alongside a PhD candidate who was more closely tied to new and recent advances and practice in the signal processing and instrumentation fields. Since my mentors each have a specific domain of expertise, I could go to the qualified person with my questions/concerns. By working on a project that involves research and application of theory, I was able to expand my breadth of understanding and then share it through presentations and papers. All these experiences make me more attractive to graduate schools and employers. Working on small projects with peers might not have afforded me a higher level of familiarity with each phase of the project, and this would have reduced the opportunities for expanding my skills. Though we all brainstormed and decided on parameters, it was my duty to see that those ideas were implemented. After I made the changes/additions I reported them to the professors for further iterations.

On the opposite side of the spectrum, working with many peers, it is often hard to coordinate schedules to see a project to completion. So, tasks are divided in hopes that the parts can come together to make a whole. This often is not a successful scheme, as the workload is almost inevitably distributed in an uneven manner. Since most of the project participants are on the same educational level, projects are often simplified and not as robust as they could be. A healthy competition can exist between students, and, because everyone has similar educational experience, it can be easier to relate to peers. Furthermore, asking faculty mentors for help can be less comfortable than discussing problems with fellow students. Both student team projects and heavily mentored schemes have their advantages, but I desired more opportunities to practice my skills in a project. The larger mentor to student ratio in our project produced the proper environment for an increased workload, leading to broader enhancement of my abilities.

Graduate perspective

In graduate school, opportunities to mentor are invaluable as preparation for both academia and industry. Many times, graduate students are entrusted to mentor less critical projects, due to constraints in their time and skill level. Interdisciplinary faculty research goals may not be clear, even to those graduate students working directly under them. An opportunity was presented me to mentor a project that had applications in both clinical and research settings. This project was time-intensive and required both my oversight and collaboration. Funnelling the project ideas from the faculty and the clinician to the undergraduate enabled me to have a clearer understanding of the project goals through the restatement of our ideas. Introducing perspectives from the clinic and the engineering labs also broadened my skills beyond a typical speciality track. As a mentor for a single undergraduate student, as opposed to several students, my focus was on improving and expanding this student's experiences in a more personal manner. The undergraduate advisee was able to brainstorm project ideas and gain insight into problem solving strategies side-by-side with more experienced researchers. With more students to oversee, this type of interaction would have been far less likely; furthermore, it is a simpler process to guide a single student toward completion of a meaningful project.

One advantage to a student team project approach is the assumption that more work will be accomplished by more students. Though this may be the case, concentrating responsibilities with a single student can often *provide more incentive for hard work and discipline. Not all students favour this type of work environment, but, for those with the time and the motivation, mentoring a more complex project endows an invaluable one-to-one working relationship with the advisee. In addition, inclusion of several faculty and/or clinical researchers enables the graduate student to view the project and its importance from a number of different perspectives.*

Faculty assessment

As noted by the students in the preceding paragraph, their assessment of the mentoring design was generally positive. Likewise, the faculty mentors on this particular project were equally positive about their experience. Since it would have been presumptuous of us to assume that no other faculty members have used and benefited from similar mentorship paradigms in senior design projects, we surveyed our JBME faculty in order to assess the mentoring practices used.

An anonymous, 50-question survey attempted to delineate the type and composition of the mentoring models used by the department faculty (sole-mentorship, multiple-mentorship, departmental, cross-departmental, inter-institutional, industry, etc.), the makeup of graduate and undergraduate student participants in mentored projects, the general level of satisfaction from the faculty participating in multiple-mentored projects, the real and perceived benefits and shortcomings of the multiple-mentored teams and, finally, an accounting of the deliverables generated. The faculty was asked to restrict responses to mentoring done for no more than five students from the previous 12-month period. Sixteen members (7 from UNC and 9 from NC State) reported on 19 student projects (12 from UNC and 7 from NC State). Three members mentored three or more students during the period, seven reported having no students and six had one project each. The data are summarized in Table 2.

When addressing the question of how prevalent co-mentored projects were, 21% of the projects were identified as sole-mentored, while 47% of the projects reported a multi-faculty mentorship. An additional 26% reported industrial sponsorship and co-mentoring. Thus, 73% of the projects had more than a single mentor. Nine of the reported projects came from laboratories hosting four or more students, while three individual student projects represented the only undergraduate activity in the laboratory. Graduate student mentorship was noted in only one project (ours) and was an unanticipated finding. JBME faculty were reported to have solely mentored, lead mentored or co-mentored in an essential role 74% of the projects (Table 2A; the JBME faculty mentorship role was not delineated by the respondents in five projects or 26%). Interestingly, when co-mentors were identified (Table 2B), those co-mentorships were primarily from other departments within the same school. However, a considerable co-mentoring role by industry was identified. Table 2C lists project outcomes as class reports and presentations, abstracted presentations, commercialization documentation and scientific papers. In 42% of the projects, national exposure was realized, whereas 21% of the projects report commercialization efforts. Faculty perceived the overall multiple-mentorship as a success (68%). 16% noted that multiple-mentorship was the only way they could have found the time to participate and 11% used it to justify their time and effort commitments. Finally, 92% of the respondents' comments were positive regarding the multiple-mentored work, whereas the lone negative comment centred on scheduling difficulties of the participants.

Table 2A. Role of BME faculty in projects

Sole Mentor on Project	21%
Lead Mentor on Project	37%
Essential Co-Mentor on Project	16%

Table 2B. Composition of co-mentored projects

Co-Mentors within Department	0%
Co-Mentors across Departments	26%
Co-Mentors across Schools/Colleges	11%
Co-Mentors with other Institutions	5%
Co-Mentors with Industry Partners	26%

Table 2C. Project 'deliverables'

Class Presentation	95%
Class Report	95%
Presentation at a Local Meeting	68%
Presentation at a National Meeting	42%
Submission of a Disclosure/Patent	21%
Preparation of a Peer-Reviewed Journal Paper	5%

CONCLUSION

We have demonstrated that project design mentoring structures are not 'one size fits all' and that alternative paradigms may better suit the needs of the students involved and the faculty that mentors them [13]. Moreover, we believe that faculty satisfaction and participation can be enhanced by using multiple mentors with distributed responsibilities instead of the traditional single mentor structure. Finally, we believe that satisfactory outcomes on a number of fronts can be achieved through the careful assembly of project teams which are composed of various mixes of faculty mentors, graduate student facilitators and undergraduate students engaged in research project work. We found that the shift in the mentoring paradigm appears to have already taken place at our institution and that the faculty participating in co-mentored projects report satisfaction. As reported by the faculty in this survey, the use of graduate students as an interface to the undergraduate is not widely practiced by our faculty. However, this may be reflection of the transitional phase of the mentoring model in use, rather than its final form, or a lack of the establishment of a formal mentoring role for the graduate student by the faculty mentor. Indeed, we predict a greater utilization of the graduate student in undergraduate project work owing to the projected increase in undergraduate BME students [14] without appreciable increases in teaching faculty [2]. While students continue to produce oral and written reports of their project work, a growing number are making national presentations and preparing patent and disclosure reports, all of which serve the best interests of students and faculty.

In summary, we believe that multidisciplinary senior design project work is of most benefit when equal attention is devoted both to the content of the project work to be undertaken by the undergraduate student as well as the composition of the mentoring team that will direct it.

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