AC 2007-1121: A FOUR-YEAR PROGRESSION OF OPEN-ENDED PROJECTS IN AN UNDERGRADUATE BIOMEDICAL ENGINEERING CURRICULUM

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A Four Year Progression of Open-Ended Projects in an Undergraduate Biomedical Engineering Curriculum

Abstract

One of the important instructional goals of our Biomedical Engineering Program is to provide students with the opportunity to develop strong, independent project skills in both the classroom and the laboratory. To accomplish this goal, the Program has developed a series of open-ended projects and laboratories that begins in the first-year introductory engineering course and extends through the senior design course. As students progress through the curriculum, the level of emphasis placed on project management and technical results is modified in accordance with anticipated student abilities.

In the first two years of the curriculum, a great deal of emphasis is placed on students' abilities to manage various aspects of projects including identifying project motivations, planning experiments, constructing experimental setups and communicating results. At the same time, students are not penalized for projects that fail to produce data as long as the team followed the appropriate design processes outlined in class. For example, in the sophomore Fundamentals of Biomedical Engineering course, students spend the semester identifying, planning, constructing and carrying out experiments modeling a physiologically relevant fluid flow phenomenon. While the students learn how to construct basic flow systems in class, they are completely responsible for the identification, design and implementation of their individual physiological model. This project provides an environment in which the students are very invested in the experimental design process yet prevents them from being overwhelmed by having to manage an entire project.

As the students enter into the final two years of the curriculum, they are presented with more open-ended projects in which they are required to perform with less guidance and in which a stronger emphasis is placed on the acquisition of valuable results. These projects include: 1) a medical device benchmarking project; 2) a fluid flow feedback control project; 3) a finite element modeling project; 4) a CAD/rapid prototyping project; 5) a cell culture project; and 5) senior design projects mentored by external experts in the biomedical field.

Overall, the four-year series of approximately eight open-ended projects provides students with extensive experience in recognizing and tackling less-defined technical projects. Since students are presented with projects in the early years that are more process driven, they have time to gain experience with project planning and execution before they enter into more results driven projects in the later years.

Introduction

Frequently, students are not exposed to open-ended projects in the laboratory and classroom until the latter part of their undergraduate engineering education. Additionally, some students are not exposed to open-ended projects until their senior design course where their progress may be limited by their lack of experience with open-ended projects. While some students may be provided the opportunity to develop open-ended problem solving skills, these opportunities may not involve actual laboratory experiments or computer simulations. To address these issues and provide students with the opportunity to become more comfortable with tackling open-ended projects, we have integrated a series of open-ended experiences into our new biomedical engineering curriculum. This series of eight open-ended projects and laboratories begins in the first-year introductory engineering course and extends through the senior design course. As our students (approximately fifteen per year) progress through the curriculum, the level of emphasis placed on project management and technical results is modified in accordance with anticipated student abilities.

Below, we provide a number of objectives for including this project sequence in our curriculum.

Objective #1: To provide students with a sequence of open-ended projects throughout the curriculum to enhance their comfort level with and abilities in open-ended situations as preparation for senior design.

Objective #2: To provide a learning environment in which the emphasis on results increases over the four years allowing students to focus more on the process of conducting projects in the earlier years.

Objective #3: To provide critical opportunities for students to effectively apply their existing knowledge and independently acquire new knowledge to synthesize and evaluate alternative solutions to complex engineering problems with specified constraints.

Objective #4: To provide our students opportunities to demonstrate their knowledge of curricular material through experimentation and problem solving involving analysis, computation, critical thinking, design and realization.

Objective #5: To enhance student and instructor interest and excitement for class projects by allowing students to play a significant role in determining project topics and specific objectives.

While the structure and motivation of each project and the exact responsibilities of the students change throughout the four year sequence, there are a number of characteristics that remain a part of each project to varying degrees. The parameters utilized in designing open-ended experiences include the following:

- Level of faculty/mentor supervision
- Level of predefined project constraints

- Importance of professional communication
- Level of student access to a wide range of equipment
- Expectation of results and functional experiments
- Expected level of out-of-class work by students
- Group versus individual project
- Expected technical complexity
- Expected level of project documentation
- Expected level of formal engineering decision making
- Time spent planning before entering the laboratory
- Expectation of students to independently learn new skills

Overall, the series of projects provides the students with a wide variety of open-ended experiences that cover a broad range of expectations with regards to project planning, experimental construction, project documentation, production of results, etc. In the remainder of this paper, we will discuss the sequence of projects and provide in depth descriptions of selected projects.

Summary of Project Sequence

In the first two years of the curriculum, a great deal of emphasis is placed on students' abilities to manage various aspects of projects including identifying project motivations, planning experiments, constructing experimental setups and communicating results. At the same time, students are not penalized for projects that fail to produce data as long as the team followed the appropriate design processes outlined in class. These projects occur in the first-year Exploring Engineering course and the sophomore year Fundamentals of Biomedical Engineering course. As an example, in the sophomore Fundamentals of Biomedical Engineering course, students spend the semester identifying, planning, constructing and carrying out experiments modeling a physiologically relevant fluid flow phenomenon. While the students learn how to construct basic flow systems in class, they are completely responsible for the identification, design and implementation of their individual physiological model. This project provides an environment in which the students are very invested in the experimental design process yet prevents them from being overwhelmed by having to manage an entire project. As the students enter into the final two years of the curriculum, they are presented with more open-ended projects in which they are required to perform with less guidance and in which a stronger emphasis is placed on the acquisition of valuable results. These projects include: 1) a medical device benchmarking project; 2) a fluid flow feedback control project; 3) a finite element modeling project; 4) a CAD/rapid prototyping project; 5) a cell culture project; and 6) senior design projects mentored by external experts in the biomedical field.

Descriptions of Selected Projects

While each student in the Biomedical Engineering Program will participate in approximately eight open-ended projects, we present descriptions of four of the projects here. These projects highlight the variety of experiences in the sequence.

1st Year Project: Engineering & Drug Delivery Seminar

In the fall semester of the first-year, all engineering students are required to take ENGR 100 Exploring Engineering which is a class designed to introduce students to the six engineering majors as well as the engineering discipline as a whole. Within this course, students take three three-week seminars which each focus on a specific engineering discipline. For biomedical engineering, the seminar focuses on the application of basic engineering principles to drug delivery. The goal of the seminar is to expose the students to the fundamental concepts associated with drug delivery and to provide the opportunity to implement these concepts in a hands-on environment (Cavanagh and Wagner, 2004). Each three week seminar has approximately 30 students in the lecture who divide into two 15 student laboratory sections in which students work in teams of three.

The nine lectures and three labs in the seminar are presented in an order which is analogous to the simple pathway of an orally ingested drug. While the early lectures focus on the possible routes of entry of a drug into the body and basic dissolution mechanics, the first lab experiment involves quantifying the dissolution of a throat lozenge under varying levels of heat and agitation. Following dissolution, the lectures focus on simple diffusion in order to describe the transport of the drug from the stomach into the bloodstream. Next, the seminar examines the mechanics of blood flow with the corresponding lectures providing a basic introduction to cardiac fluid mechanics including cardiac physiology, Bernoulli's equation, Reynolds number and flow resistance. In the associated fluid mechanics lab, the students utilize an assortment of fluid flow equipment to design and build a recirculating flow system for examining how pressure and flow resistance in a tube is affected by flow rate, tube length and degree of constriction.

The open-ended project in this seminar focuses on the third lab section of the seminar where the students are given the following objective:

> To design a new experimental setup based upon the first two experiments to permit the examination of the combined effects of the recirculating flow and lozenge dissolution on the overall transport of the drug.

For most of the students, this exercise is the first of their educational career where they are completely responsible for planning and executing an experiment. While some of the students recognize and excitedly accept the challenge, others can be quite intimidated by the process.

Prior to coming into the lab, they are given a class period to meet with their partners and plan their final experiment. They are provided with a few restrictions in order to keep the projects manageable. First, they are restricted to only using the lab equipment they utilized in the prior two weeks. Second, they must have a sketch of their experimental system reviewed by the instructor before coming into the lab period. Third, they must think ahead of time as to what data they will record. Next, they must plan their system such that they can construct it and run the associated experiments in two hours or less. In their final written reports, the students are required to document their experimental plan, present their results and provide an analysis of the results and the experimental setup. Examples of how students integrate the flow loop with the dissolving lozenge in order to model drug delivery include:

- poking holes in the flow tubing and submerging it in the beaker with the dissolving lozenge
- branching the flow path such that part goes into the lozenge beaker and part simply recirculates.

Overall, this open-ended project is designed to provide first-year engineers with the opportunity to not only learn new concepts and lab techniques, but also to utilize their own creative abilities to plan a new experiment. As the level of technical complexity in these projects is not high, the primary motivation for providing this experience is to demonstrate to the students the importance of open-ended projects and their relevance in the engineering field.

2nd Year Project: Experimental Analysis of Flow in Physiological Models

While the students received a brief introduction to open-ended projects as first year students, they are provided with a more comprehensive experience at the beginning of the second year in their Fundamentals of Biomedical Engineering course. On the first day of this course, they are told that they will be working throughout the semester on a team project for which they will be responsible for identifying the motivation, planning and constructing the setup, and acquiring and analyzing the results. The overall goal given to the students is:

> To proceed through the open-ended process of designing a physiologically relevant recirculating fluid flow system to acquire and interpret experimental measurements.

In summary, each team will use a recirculating flow system with a few prescribed components including two pressure transducers. The projects will be individualized by each team identifying a physiologically relevant flow phenomena that can be experimentally modeled by creating a test section between the two pressure transducers. Another component of the class that is purposefully put in place is that all of the hands-on laboratory exercises in the course focus on providing the students with guidance on how to operate a majority of the equipment that might be used in the projects. While they do not realize this on the first day, they do indeed realize it later in the course as they begin working in the lab on their projects. The students are told that each experiment must have the following characteristics:

- Each design must contain two pressure transducers, one rotameter and one pump in a recirculating system.
- As the pressure transducers only provide output voltages, each group must design and implement a calibration method for converting the voltages to units of pressure.
- The voltage output of the pressure transducers will be acquired using a PC/Data Acquisition system and LabView program written by the group.
- After designing and planning the system on paper, each group will construct their system in the laboratory.
- Once the system is assembled and tested, data will be acquired and analyzed in order to quantify the effects of parameter changes to the system.

While there is apparent excitement for the projects, we also frequently observe students saying "How can we plan and execute an entire project? We're only sophomores." To address this concern, our primary goal is to provide them with an open-ended project opportunity where they can gain exposure and confidence with these types of projects but also feel that there is a safety net built into the process. In fact, we tell them that if a team generates excellent technical results but fails to adequately follow the project planning process, their project will not be viewed as successful. Furthermore, they are told that if after all of their planning and hard work their experiment fails to produce quality results, they can still receive a high grade. In the end, we want each team and each student to have a deeper understanding for and appreciate of the open-ended project process without being overwhelmed by the pressure of producing results. While this course is typically team taught by two faculty who divide the course in half based on content, both faculty participate in advising the project teams. Furthermore, as we have had enrollments ranging from 13 to 17 students, teams are typically comprised of 2 to 3 students.

Probably the most frustrating part of this project from the students' perspective is the on-paper planning process. While the students would prefer to get right into the lab and begin constructing their experimental apparatus through more of a trial and error method, we require the teams to perform a fair amount of on-paper planning before entering the lab. Our motivation for this is that in their future careers they will likely be required to carefully plan and design a system or process before ever entering a laboratory. In this planning process, students are required to produce a document that includes items such as documentation of equipment needs, a hierarchical list and description of technical goals, a hypothesis statement, a sketch of the system, a list of parameters to be varied, a list of variables that can be controlled and a discussion of anticipated results. Upon completing the planning process about half way through the semester, the students are basically let loose in the labs where they have 24 hour access to the facilities. While this type of student access may appear to be risky, we have had almost no supervision issues in the lab primarily due to the number of students in the class and safety and security measures put in place, e.g, three different codes are needed to access the laptops. The students are made aware of the opportunity they are being provided and are fully informed of the consequences to their team project should anything go wrong due to poor decisions on their part.

In order to ensure that all teams make adequate progress throughout the semester, the students are provided with a list of periodic assignments and corresponding due dates. Additionally, each team will have scheduled meetings with the instructor to discuss design challenges and how to troubleshoot specific problems. In order to document their process, each team is required to maintain a design log according to specific guidelines. As this is the best documentation of their process, each team is informed that if their design log does not meet expectations, they will have to submit an additional 30 page technical report at the end of the semester. Issues with design logs rarely arise due to this policy. As the semester nears the end, there is commonly a strong effort put forth by the students to make their systems work. The two deliverables from the projects are a 20 minute group oral presentation in addition to a four page paper in standard IEEE format. No extensive written report is requested in order to keep the focus on the experimental process. Examples of student final projects include:

- Examination of aneurysm mechanics with balloons placed in the flow path
- Examination of the effects of particles in flows by mixing microspheres into the liquid

- Examination of plaque build up by coating the inside of sections of tubing.

While the students tell us that this course has required more time than any other they have taken, they also say it has been one of the best. One student contacted the instructors via email with the following comments: "Thanks for the semester, it was my favorite course I have taken thus. I think I can agree with Kyle when saying I spent the most time on it but got the most out of it and enjoyed it the most." Perhaps the best motivating factor in the project is that each team chose its specific topic and is therefore personally invested and responsible for making it work. Although we frequently remind the students that success is possible without results, they remain very focused on making their projects work despite their increasing stress levels. Their long hours in the lab are not required by us and are simply motivated by their own desire to accomplish the objectives they themselves set forth. In general, most of the designed systems do indeed work at the end of the course and produce valuable data. When asked to look back over the semester and recap what they have done, the students are generally amazed at their accomplishments and quite proud. Most of them now know that even though they are only sophomores, they can indeed accomplish a great deal without detailed explicit instructions.

3rd Year Project: Computational Modeling of Physiological Phenomena

Up until the spring of the junior year, most of the projects on which the students have worked have been in a group format. In order to provide each student with the opportunity to work on his/her own open-ended project, students are assigned a finite element modeling project in their Biotransport I course which is their primary fluid mechanics course. This course is taught by a single instructor and has had enrollments of 13 and 15 students. The primary objective given to the students is:

> To identify, set up and solve a two-dimensional, steady, biomedically relevant fluid mechanics problem that provides physical insight to the actual physiological phenomenon.

The primary deliverables for this project are periodic progress memos and a final conference style poster to be displayed in a public poster session. In relation to the open-ended projects from the first two-years, this is the first project in which results and associated physical interpretations are critical and mandatory in order for a student to succeed. Furthermore, students are not required to maintain any sort of design log for their efforts although they are strongly encouraged to do so in order to keep their efforts on track. In this project, we are attempting to begin to encourage a more independent and less faculty-guided project process by providing faculty assistance and guidance in a less formalized manner. In designing this project, we anticipated and addressed a number of student concerns that could arise throughout the project including:

- How can I do this since I do not know the software package?
- With no partner in the project, how can I be sure my model is correct?
- How am I going to manage my own time when I have always been in teams for projects?
- It is not fair that my project is harder than those of other students

- I've never had to make a technical poster before.

As this is the students' initial exposure to finite element modeling, they are not only challenged by identifying the motivation for the project and executing the project, but also with learning the software package in group and individual settings. In order to assist the students in the learning process, a series of classes and labs are dedicated to allowing the students to work in groups on solving predefined computational models in the first part of the course and to work on their own projects in the latter half of the course. In addition to assisting them in making progress on their projects, the use of lab time for the projects also reduces the amount of out of class time the instructor needs to dedicate to the projects. Beyond these sessions, each student needs to independently learn more of the software's capabilities depending upon his/her project topic.

In making the students work by themselves in this project, we hoped to accomplish a few goals. First, we wanted to provide students the opportunity to demonstrate their individual abilities especially if group work is not one of their strengths. Second, we wanted each student to experience individual accountability for each assignment and the final deliverables. Finally, we wanted each student to experience managing a semester-long project by him/herself.

To address the anticipated concerns, we assured all students that the degree of difficulty in each project would be taken into consideration. For example, a student with a simpler model would be expected to provide more in-depth results analysis while a student with a more complicated model might only have basic results analysis. Additionally, we provided sufficient poster preparation guidance for each student as some had made conference posters before and others had not. Overall, we attempted to provide each student with the opportunity to succeed. Examples of student projects include:

- Analysis of flow through bypass vessels
- Analysis of the fluid mechanics in aneurysms
- Analysis of the effects of plaque build up on blood flow

After implementing this project for the first time in spring 2006, we determined that the combination of the open-endedness of the projects and the requirement that students work individually can create various valuable challenges for the students. First, while all of the projects have some basic characteristics in common, each possessed unique qualities requiring each student to learn slightly different modeling approaches and software capabilities. Due to this, each student had to become self dependent and become the 'expert' in that area of the modeling as there were no partners to consult. This exercise was a direct example of students independently learning technical information on their own and implementing it into a technical project. The second challenge experienced by the students was the physical interpretation of the simulation results which represented a significant portion of the project grade. As each model was different, each produced results that had different physical meaning and required students to consult a wide rage of books and journal articles.

At the end of the projects, while many of the students agreed that the projects were "very challenging", they also expressed their appreciation for the projects in that they "provided a way to visualize detailed problems" and "allowed practical application of knowledge". Furthermore, the students repeatedly expressed how they valued the opportunity to choose the topics for their projects. While each student experienced some of the frustrations of carrying out independent, open-ended projects, each of them also displayed a strong sense of pride at the final poster presentation that was attended by numerous engineering and science faculty.

4th Year Project: CAD/Rapid Prototyping Fabrication

In the fall of the senior year, all biomedical engineering students take a half-credit Research Methods II course that has been created to provide students with an introduction to more involved laboratory based skills. In fall 2006, the course focused on computer aided design (CAD) with fabrication and cell culture with statistical analysis. As we anticipated that the CAD-fabrication project would likely be valuable to many senior design teams, we chose to make this the focus of the first part of the course. Since many of the design teams have utilized CAD-fabrication in their projects, we feel that our just-in-time approach has been effective in that they were able to learn a new skill and readily implement it in another course. For the course, the 13 students were divided into teams of 2 or 3 and were provided guidance from the instructor who was assisted by technical staff experienced with CAD-fabrication and cell culturing. Below, we present a more in-depth discussion of the CAD-fabrication projects

In general, the objective of the fabrication project is to provide an environment in which the students are guided in teaching themselves a CAD software package (SolidWorks) and fabricating designs using rapid prototyping and machine shop facilities. As students are not required to have experience with any of this technology before entering the class, the material is completely new for nearly the entire class. In order to complete the project, students are guided through a series of tutorial-like exercises for SolidWorks and are provided instructions on how to operate the prototyping and machine shop facilities. As these skills develop, the students begin working in teams on their projects for which they are provided the following objective:

> To utilize CAD and available fabrication technologies to create a biomedically relevant fluid flow chamber that permits the examination of flow patterns.

Each device consists of two parts, one of which is fabricated through prototyping and the other is made in the machine shop. After fabrication, the two parts are to be assembled together to make the flow chamber. Once assembled, the flow chamber is tested and flow visualization experiments are conducted to analyze the fluid mechanics in the device.

In order to focus the projects on learning the new fabrication skills and constructing and testing the flow chambers, students are required to base their designs on the two-dimensional finite element models they developed the previous spring in Biotransport I. As mentioned above, those projects are done individually. To take this into account in the group fabrication projects and to ensure that all students are able to use SolidWorks, each student is tasked with creating a 3-D CAD design of his/her own 2-D finite element model. Next, each group chooses one of the designs to actually prototype and then machines the lid from an acrylic sheet. As a final step, each group implements a flow visualization technique, e.g., dye injection for visualizing streamlines.

Overall, the students have numerous tasks and objectives to accomplish through their own decisions and self-guided learning. Due to the approximately six week time constraint for the projects, we focus the process on their prior finite element projects in order to save time on project identification. This permits the students to immediately focus on the creation of the CAD designs following the tutorial exercises. Similar to the previously discussed finite element projects, each CAD design project has unique qualities that require its designer to learn aspects of SolidWorks that other students may not need to learn.

Assessment

As this sequence is new to the curriculum and will not be fully implemented until the conclusion of our first senior design course in spring 2007, we are currently in the process of designing appropriate assessment mechanisms to evaluate the effectiveness of this aspect of our curriculum. These assessment mechanisms, both direct and indirect, will permit us to not only examine the educational value of these open-ended projects but will also provide our Program with the opportunity to conduct assessment as related to various accreditation requirements including ABET Criterion 3a-k. We plan to assess the value of each project within each course as well as the value of the entire sequence within the curriculum. As we intend to implement assessment measures with our first graduating class in spring 2007, we plan to present the initial assessment results at ASEE in June 2007.

Conclusion

As mentioned in the introduction, one major goal of implementing this sequence of projects is to prepare the students for the project that is the most open-ended of all, i.e., the senior design project. Ideally, this sequence of projects provides each student with the opportunity to develop an extensive design and project oriented tool kit from which he/she can choose a wide range of tools to accomplish a wide range of tasks in senior design. These skills and tools cover a variety of design areas including: project identification, hypothesis creation, project planning, experimental apparatus construction, individual confidence, device fabrication and results presentation. While we realize that the students may not need to utilize every skill and tool acquired, we also hope that the students will encounter few situations where their progress is limited by the skills and tools in their toolkits.

As of early 2007, our first class of thirteen students has progressed half way through their year-long design process aimed at providing the students an opportunity to design devices and systems addressing relevant medical or engineering problems under the guidance of an external mentor. At this midpoint in the projects, all of the teams have identified relevant biomedical topics, defined objectives, and created preliminary solution strategies for five distinct projects. Two of the five groups have even produced initial rapid-prototype models to share with external mentors.

While these types of projects do require enhanced levels of interactions between students and faculty, we feel that the anticipated educational benefits for our students are of great importance. Since our Program focuses on undergraduate education, these types of open-ended projects are directly in line with our mission. Additionally, as we do not plan significant enrollment growth in the near future, the amount of additional faculty workload is kept manageable through the small class sizes.

Overall, the four-year series of approximately eight open-ended projects provides students with extensive experience in recognizing and tackling less-defined technical projects. It appears that allowing students to chose and determine project objectives greatly enhances student enthusiasm, student effort and student pride. Furthermore, since students are presented with projects in the early years that are more process driven, they have time to gain experience with project planning and execution before they enter into more results driven projects in the later years.

Bibliography

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