

## **AC 2008-1221: RESEARCH TRAINING OF UNDERGRADUATES THROUGH BIOMEMS SENIOR DESIGN PROJECTS**

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# Research Training of Undergraduates through BioMEMS Senior Design Projects

## Abstract

Bio Micro Electro Mechanical Systems (BioMEMS) is a multidisciplinary research field that closely integrates engineering with physics, chemistry, and biology. This emerging technology has an innovative effect on many areas of science and engineering. Research in BioMEMS generally occurs at the graduate level, due to its multidisciplinary nature. At the University of Cincinnati we have developed a number of courses in order to introduce graduate students to this topic. However, little focus has been given to the undergraduate experience. To address this concern, graduate students along with their faculty advisor in the Electrical and Computer Engineering Department have been using the required senior project to teach research methods in order to give undergraduate students a chance to experience BioMEMS-related research. This paper will discuss some of the research-oriented senior projects in the BioMEMS field as examples. A unique aspect of these projects is the focus on extended problem-based real-world learning examples.

The senior design project gives students a unique opportunity to undertake a research project similar to that which would be expected in a Masters level program. This allows preparing to be more successful as they move onto graduate research studies. Throughout the year, students submit periodic progress reports and give presentations summarizing their research efforts, current problems, and future directions, providing an opportunity for real-time feedback and tailored guidance leading to more successful project outcomes. The undergraduate students who worked on the projects not only completed their research project goals, but also submitted abstracts of their work to international research conferences, and two students extended their research as NSF Research Experience Undergraduate (REU) students through the summer term prior to continuing on to graduate school. The success of these research-oriented senior design projects is encouraging and we propose extending this opportunity to motivate students enrolled in related programs such as biology, chemistry, and other engineering disciplines.

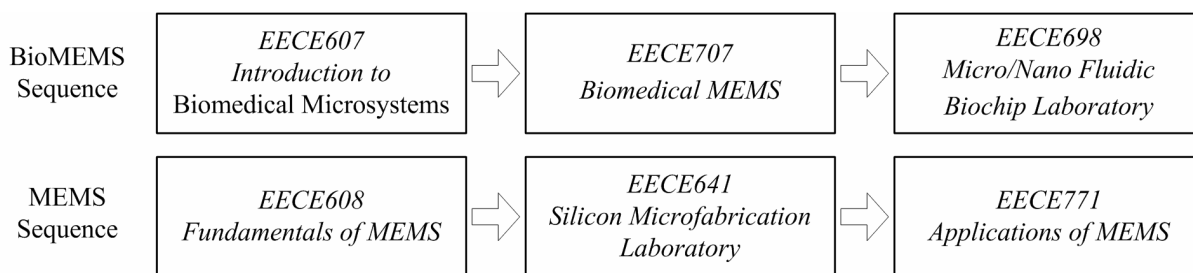
## I. Introduction

Micromachining or Micro Electro Mechanical Systems (MEMS) technologies are considered an enabling technology that has a revolutionary impact on many areas of science and engineering.<sup>1</sup> MEMS technologies are now being applied to health monitoring, diagnostics and therapeutic applications, which are frequently referred to as Biomedical Microsystems (BioMEMS). BioMEMS research includes biological, biomedical, biochemical, and pharmaceutical analysis and synthesis using MEMS-based microsensors and microsystems.

While the BioMEMS technologies have dramatically altered biomedical, pharmaceutical, and environmental research, they are yet to be successfully transferred to the undergraduate curriculum. Because of the multidisciplinary nature of BioMEMS and the background needed to conduct research, BioMEMS courses have traditionally been offered at the graduate level only

and often require prerequisites not normally included in a typical electrical engineering curriculum.<sup>2</sup>

At the University of Cincinnati the state-of-the-art emerging MEMS and BioMEMS research has been integrated within the graduate and upper-level undergraduate electrical engineering curricula. The current courses are outlined in Figure 1.<sup>3</sup> These courses provide students from diverse disciplines with the ability to design and fabricate complete microscale and nanoscale systems. The MEMS sequence provides principles and applications of microfabrication and microsystems, while the BioMEMS sequence provides biomedical applications of MEMS and microfluidics. Typical enrollment in these courses ranges from approximately 12 students in the graduate courses (700-level and above), to about 30 students in the dual-level lecture courses (600-level). In these courses, enrollment has increased beyond the initial target audience of the Department of Electrical and Computer Engineering. It now includes students from mechanical engineering, environmental engineering, biomedical engineering, and chemistry.



**Figure 1.** MEMS and BioMEMS courses offered at the University of Cincinnati.

Fifth-year undergraduate students (seniors) in the Electrical and Computer Engineering Department take a sequence of 3 senior capstone courses for a total of 9 credit hours in their senior year.<sup>4</sup> Typically, students self-organize into teams and select a project of interest. They may choose a variety of projects proposed by industry, community organizations, professors, co-op employers, or themselves. All teams meet with the course instructor and complete a series of deliverables to specify and document their projects. Each team has a technical advisor with particular expertise in the project area who supervises their progress.

A project in BioMEMS or Biomedical Microsystems gives senior students a cutting-edge research experience, allows them to work with graduate students and faculty, and exposes them to problem-based learning experiences not covered by their curriculum. To give undergraduate students a chance to experience BioMEMS-related research, graduate students along with their faculty advisor have been using the required senior project to teach research methods.

The paper will discuss details of two senior projects in the area of BioMEMS. Both projects involved teams composed of both seniors and graduate students. Problem-based learning with advanced graduate students continued in an active laboratory experience.<sup>5</sup> Both senior projects were designed to give undergraduate students an opportunity to introduce and experience a multidisciplinary research project, which is common to the fields of MEMS and BioMEMS. Furthermore, team projects provided an opportunity for peer learning, teaching, and tutoring as well as expository instruction from faculty members.

## II. Typical project structure

A typical senior project in BioMEMS consists of three quarters, and an additional fourth quarter as an advanced optional research during the following summer. Throughout the course of their projects, senior students are required to submit short progress reports and give presentations summarizing their research efforts, current problems, and future directions. These activities help them improve their scientific writing, presentation and communication abilities. The general objectives and activities for each quarter are as follows.

*Fall quarter* provides information on basic research procedures. Reading, summary, and discussion of research papers are used as an active learning exercise to motivate students and introduce them to the state-of-the-art. This literature review compliments student enrollment in the “Fundamentals of MEMS” and “Introduction to Biomedical Systems” courses (see Figure 1). The students are encouraged to continue the MEMS and BioMEMS sequence of courses to help them better understand the MEMS fabrication technologies and BioMEMS systems. At the end of the quarter, students submit summaries of their literature review.

*Winter quarter* emphasizes project-specific advanced understanding and techniques. Weekly meetings with their graduate student mentor and bi-weekly meetings with the faculty advisor are used to help senior students to advance the project with tailored guidance. These meetings also provide feedback to the graduate mentor and faculty advisor regarding student progress, and offer an opportunity to identify and trouble shoot problems. During this quarter students begin to work in the faculty advisor’s laboratory with their graduate student mentor’s supervision.

*Spring quarter* emphasizes mentored laboratory activities to fabricate and optimize their project design. The fabrication process and data analysis are performed with the graduate student mentors. At the end of this quarter, senior students prepare their final project report and presentation.

*Summer quarter* is optional and is focused on advanced research activities. Senior students are offered an opportunity to extend a successful senior project and prepare an abstract for submission to a technical conference. Depending on availability, some students are offered an NSF Research Experience Undergraduate (REU) supplemental funding during this quarter.

## III. Case studies

### Case 1: Microfluidic mixer for mixing particle based flows

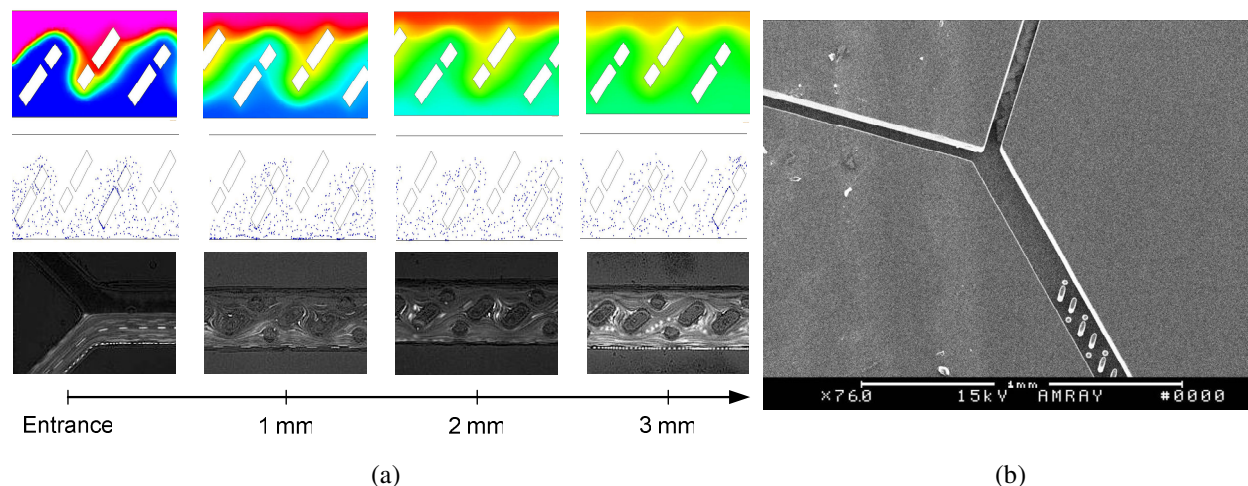
The objective of this senior project was to introduce undergraduate students to the rapidly emerging field of micro/nano fluidics. The goal of the project was to design a microfluidic mixer capable of efficiently mixing particulate-based flows. Rapid mixing of macromolecular solutions presents a significant challenge in microfluidics. Despite the great success of mixing pure liquids, in real-world applications micromixers need to mix particulate flows such as blood, cells or microorganism suspensions. Mixing of microparticles with reagents is also required to increase reaction probability for many particle-based assays for detection of biological molecules in microfluidic systems. Thus, successful development of a micromixer capable of passively

mixing particulate flows in a short distance is of a significant interest to the microfluidics and Lab-on-a-chip (LOC) research communities.

During the course of this project, students were familiarized with computational fluid dynamics (CFD) tools for modeling microscale flows. Following the design and modeling of the micromixer, senior students used the University of Cincinnati's state-of-the-art cleanroom facility to fabricate the micromixer in polydimethylsiloxane (PDMS) polymer. The project exposed students to polymer microfabrication technologies that are beginning to dominate microfluidics. Finally, students characterized the fabricated devices using an epi-fluorescence microscope for visualizing particle flows.

The graduate student mentor working with the undergraduates prepared tutorials which helped the students get acquainted with the modeling software.<sup>6</sup> The tutorials initially helped students to model flows through simple geometries, such as the Y-mixer, followed by more complex geometries, such as the Tesla mixer, and analyze the results to calculate mixing. By the end of the fall quarter, students were required to finish reviewing the tutorials and were also given relevant literature in the forms of scientific papers and text books to gain better understanding of microfluidic basics and polymer microfabrication techniques, updating them with the current state-of-the-art in micromixer development.

In the winter quarter, questions regarding the modeling software and trouble shooting instructions were discussed during weekly meetings to keep the students' progress on track. Periodic brainstorming sessions with senior graduate students during the early design development stages helped the students optimize their micromixer design. By this time, the undergraduate students showed good aptitude for research, demonstrating novel micromixer designs, and revealed that the literature reviewed during the fall quarter had helped them develop lateral thinking. By the end of the winter quarter, the students had already designed and modeled the optimized micromixer design for mixing particle flows and were ready to fabricate them.



**Figure 2.** Representative images of the developed micromixer. (a) Results showing the simulation and experimental cross-section images of the microchannel indicating fluid and particle mixing downstream, (b) scanning electron micrograph of the fabricated micromixer.

The first few weeks of the spring quarter were spent fabricating the designed micromixer in PDMS polymer. Although the undergraduate senior students working on this project were prepared and trained them for working in a clean room environment, most of the fabrication process for this project was carried out by the graduate student working. This approach was taken for two reasons. First, demonstrating the process saved time and ensured timely completion of the project. Second, due to the high costs associated with using the cleanroom, it was uneconomical to have undergraduate students use the facility for one quarter. Following fabrication, the students tested the microfluidic devices using the microscope facilities available in the laboratory. The students spent 3 weeks testing the devices with particulate laden flows and 2 weeks analyzing the results. Figure 2 presents example images of the developed micromixer discussed in the current case.

As a completion to the project and practice for graduate school, students also submitted an abstract to a conference in the field of microfluidics.<sup>7</sup> One of the students working on the project extended the research as an NSF REU student during the summer quarter in the research advisor's laboratory. Since the research conducted on this project was for a biomedical application, the student was motivated by the experience to later pursue a Ph.D. program in biomedical engineering at another university.

## **Case 2: Electrochemical sensor system for nitrate monitoring in water**

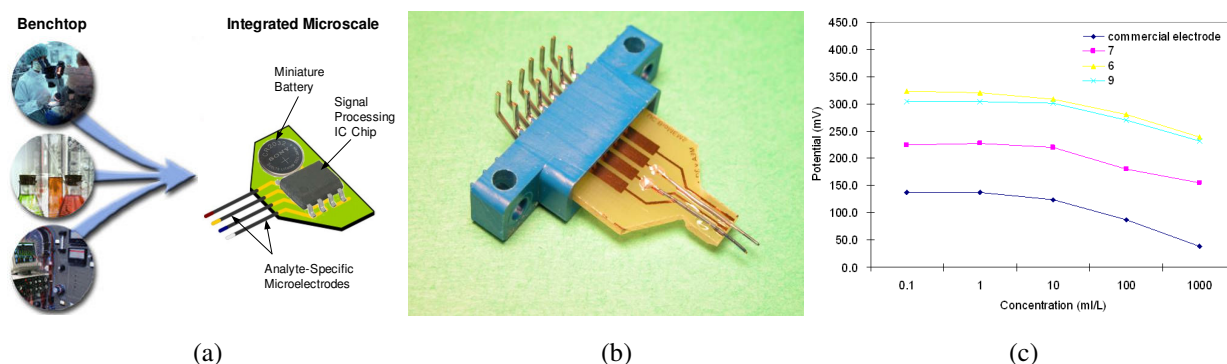
The objective of this senior project was to develop a new nitrate ion selective microelectrode array sensor system for *in situ* monitoring in environmental applications. High levels of nitrate (>10mg/L) from agricultural and mining industries affect the quality of water and can cause serious public health problems. Therefore, there is clearly the need to monitor nitrate *in situ* in drinking water, wastewater, and water distribution systems. However, commercial nitrate sensors suffer from short lifetimes, require constant calibration to maintain accuracy, are difficult to manufacture, and are costly.

This senior project was designed to give undergraduate students a chance to experience multidisciplinary collaborations with two research groups. Two senior student teams worked on the development of a sensor system, consisting of a nitrate microelectrode array sensor and a data acquisition chip. Two faculty members, specializing in BioMEMS and biomedical data control, supported and coordinated the students and graduate students mentors. Two specific aims were (1) to develop a new nitrate ion selective membrane, and (2) to design the data acquisition circuit board. This effort was parts of the National Science Foundation (NSF) funded project to develop a multi-analyte microelectrode array sensor system.<sup>8,9</sup> Graduate students involved in this project became mentors to help senior students achieve their goals.

In the fall quarter, senior students started to research topics by finding information in the library and online resources. The graduate student mentor introduced *Compendex*, *INSPEC*, *IEEEExplore*, and *SPIE Digital Library* databases to help students find and filter scholarly articles focused on specific topics that would update them with the fabrication and characterization of an advanced sensor system working. Current sensor problems and new membrane sensor requirements were defined based on their literature reviewed. Attendance of the research group meetings was encouraged to enable familiarity with a research environment and discuss the

project with other research group members. The student mentors were used more as learning tools, training students on various lab equipments necessary for the project.

In the beginning of the winter quarter, communication problems were realized between students and mentors, and even among senior students which commonly occurred in multidisciplinary projects. Regular research meetings between two teams along with the graduate mentors helped improve the communication among senior students, thus ensuring the timely completion of the project. The concept of a multi-analyte microelectrode array sensor system (Figure 3 (a)) was given to senior students as a big picture to have a clear idea for the final goal. A new matrix membrane was chosen from among several possible membrane materials after considering various fabrication methods, budget limitations, and available timeline. At the end of winter quarter, prototype nitrate ion selective sensor was successfully fabricated, and the optimization of the fabrication process was followed to increase sensor sensitivity. The fabrication process allowed them to apply their knowledge to develop an advanced real-world sensor system. Due to safety issues, laboratory procedures of the senior students were achieved with a graduate student mentor. Current problems and future directions were discussed not only with the faculty advisors and graduate student mentors, but also with the other group members to provide real-time feedback and tailored guidance in the group meetings.



**Figure 3.** Representative results of the electrochemical nitrate sensor system. (a) The concept of microelectrode array sensor system, (b) new membrane nitrate sensors with the edge connector, and calibration curves with various concentrations (c).

By the spring quarter, modified nitrate sensors were successfully fabricated (Figure 3 (b)), and characterized with the signal conditioning low pass amplifier at the range of 0.1-1000 mg/L sodium nitrate (Figure 3 (c)). The test set up for characterization was designed senior students with graduate student mentors. The new nitrate membrane ion selective sensors exhibited excellent sensitivity at high nitrate concentration. The undergraduate students showed good experimental, effective presentation, and communication skills with sufficient understanding and knowledge of their research topics. At the end of spring quarter, senior students prepared and performed a final senior project presentation well. A team-based project allowed peer learning, teaching, and tutoring as well as expository instruction. Through multidisciplinary collaborations project, senior students could experience not only BioMEMS research but also the importance of safety issues, improvement of communication skills between team members and activities, and careful schedule planning to reduce dead time. After finishing the two projects,

one of three students extended the research as an NSF REU student during the summer quarter and two students were accepted by the graduate school.

#### IV. Student Assessment

In the fall quarter, each student enrolled in the ECE senior design capstone sequence was required to write an essay assessing his or her readiness to undertake their chosen senior design project, and in particular addressing how the project embodies the culmination of classwork and co-operative education experience from preceding years. Excerpts from student essays are given here to illustrate how the students view their past educational experiences and their anticipated readiness to initiate a research-based senior design project. One student cited both previous and senior year electives:

- *Curriculum experience prior to this year has been crucial for understanding fundamental physics in order to design a microsensor. Since the field of MEMS is a conglomeration of many fields, freshman chemistry was also important ... I am taking Environmental Engineering electives to obtain more coverage of chemistry. These are in the field of water quality and physics. These classes will help with the environmental chemistry involved in our project. Most importantly, this quarter I am undertaking the MEMS sequence which will teach me additional fabrication techniques.*

Other students cited the importance of co-op (industry and research) experience to successfully complete their senior design projects:

- *As an Electrical Engineer I have experience working in Information Technology, Controls Engineering, and Sourcing. ... In IT, I learned about project management and risk management. In Controls Engineering, I learned to be persistent, systematic in solving problems, and attentive to details. And in Sourcing, I further developed my leadership and communication skills to steer the project on the road to success. And at different stages of my senior project I will apply these different skills to enable me to achieve the desired outcomes. Our senior project is currently at the conceptual stage thus required me to apply more project and risk management skills. When we begin working in the lab and fabricating the sensor, I will need to apply my troubleshooting skills.*
- *My last four co-op quarters will help greatly in being able to be successful with my project. I spent two quarters at the Cleveland Clinic Foundation and it is there that I learned about Biomedical Engineering research as well as how it is being pursued by both academia and industry. ... During my last two co-op quarters at Robert Bosch GmbH in Germany I was able to get a different perspective on research methods and also gain experience in the cleanroom environment while working with silicon photolithography. Although I will not be working with lithography, the basic concepts of microfabrication will apply as I build the micromixers winter quarter.*

In the spring quarter, each student wrote a final self-assessment essay that details what they have learned from conducting their senior capstone project. The impact of research training was evident in their technical mastery of the subject and their tangible accomplishments as well as



their professional growth as members of a research team. Both technical and non-technical skills have been acquired by the students:

- *Over the past 3 quarters, I learned how to monitor levels of substances in water using oxidation and reduction potentials. The physics behind Gibbs Free Energy and understanding how electrons are transferred from one molecule to another. How to test, and setup a test for these procedures, was additionally learned. This is critical, because good data is important if you want results that have merit. Lab safety and procedures were also learned.*
- *On the less technical side of things, I learned how to manage what little time you have to perform and document your work. Efficient management is important, as well as superior team work, and communication. In order for the project at hand to be accomplished, these and many other qualities of professionalism are required.*

As a result of the acquired research training, several of the students opted to continue their educations in graduate studies. One student acknowledged the impact of the training:

- *The main thing I learned during this project was the CFD ACE+ software package. I had no experience in modeling microfluidic systems in any software, so the entire process of simulating the channels was new to me. I learned how to build the micromixers and what to look for when testing them. I was able to expand my research skills which will help greatly as I continue on to work on my Ph.D. at the Ohio State University in the fall. I learned how to manage a project from start to finish and what is required to get it done.*

## **V. Discussion**

Senior research projects conducted in the laboratory provide an excellent experience and opportunity for undergraduate students, graduate students, as well as their advisor. Undergraduate students are given the opportunity to gain hands-on experience in the research area of interest under the guidance of a faculty advisor and graduate students. The value of practical experience cannot be underestimated, as it contributes to the development of expertise that is simply not available by reading a textbook. This experience allows undergraduates to familiarize themselves with the background, methodology, and the culture of working in a laboratory. As the constraints and goals of the projects are outlined, the students are exposed to a real-world project cycle; applicable to an academic as well as an industry setting. This experience prepares students for a research environment and allows them to make better decisions about their professional future.

Senior research projects are also advantageous for graduate students. It gives them an environment in which to learn how to effectively mentor students and manage a project team as they are guided by their research advisor. A graduate student had the opportunity to mentor senior students and to be mentored by faculty advisor for teaching activities simultaneously. Compared with mathematics, physics, chemistry, and biology, it is difficult for graduate students in electrical engineering to get a chance to teach because most of works focus on research. This opportunity allows them to practice their skills in teaching, time management, delegation of tasks,

and many others. These skills are crucial for future faculty or a career in the industry. One of the graduate student mentors in this project was enrolled in a Preparing Future Faculty (PFF) program at the University of Cincinnati.<sup>10</sup> Senior projects allowed the graduate student to apply the concepts learned in the PFF courses and experience more teaching activities with students at various educational levels. As graduate student mentors, we learned how to gradually introduce the material, rather than overwhelming the undergraduates. It was also critical to identify the needs and previous educational experiences of the individual students in order to outline a customized work plan. The work plan included both short-term and long-term goals as well as the timeframe for reaching those goals. The goals were revisited and revised accordingly with the students on a quarterly basis. Finally, as mentors it was essential to contribute to instilling the skills that are useful in the students' future careers and/or graduate studies.

Lastly, it is also advantageous for the research advisor to support senior projects. It provides a chance to mentor undergraduate students working in a laboratory and to identify and address their strengths and weaknesses. The professor gets a chance to pre-select strong undergraduate students to work in the laboratory on summer research projects (such as REU supplements), as well as subsequent research. For example, over the last eight years 17 senior students in 10 senior projects participated in this program; more than half of these students (nine) continued on to pursue graduate degrees at the University of Cincinnati or other universities. This initial success is very encouraging and points to the value of research training of undergraduates through senior design projects.

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