2006-566: A BIOMEDICAL MICROSYSTEMS COURSE FOR ELECTRICAL ENGINEERS

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A Biomedical Microsystems Course for Electrical Engineers

Introduction

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

To expose our undergraduate seniors and first-year graduate students to the emerging area of Biomedical Microsystems, *ECES607: Introduction to Biomedical Microsystems* course was offered at the University of Cincinnati. The course focused on the basic principles of MEMS and microsensors, and their applications in biology and medicine. Topics covered included biochips and lab-on-a-chip devices, microfluidics, biosensors, material biocompatibility, cell and tissue engineering, and point-of-care medicine, including discussions of commercially-available systems. Following last year's course offering, surveys were conducted to assess student's opinions on the course content, delivery, and structure. We reported our preliminary results last year.[1] Now, in this recent offering, the course has been modified to address student feedback. This paper reports on modifications to the course and draws comparisons with the last year's student feedback and course evaluations.

The Course

The "Introduction to Biomedical Microsystems" course introduces electrical engineers to the rapidly emerging area of BioMEMS, and was described in detail previously.[1] Briefly, the course was designed to be ten weeks long, three hours per week, consisting of twenty 75 min lectures. As a 600-level course it was dual-level, intended for the undergraduate seniors and first year graduate students in the Electrical Engineering program. There were no prerequisites other than senior class standing. Also, no background in MEMS or biomedical instrumentation was assumed or required.

The objective of the course was to expose students to biomedical microsystems and to teach them fundamental principles of MEMS applications in biology and medicine. Topics covered included BioMEMS fabrication, microsensors for medical applications, biochips and lab-on-a-chip (LOC) devices, microfluidics, biosensors, material biocompatibility, and cell/tissue engineering. These topics are listed in Table 1.

The course was offered in parallel with the *ECES608: Fundaments of MEMS*, and thus was a first exposure to MEMS for many of our students. Although topics of this course cover microsystem design and fabrication, we did attempt to provide students with brief background in

Table 1. Topics covered in the "Introduction to Biomedical Microsystems" course.[1]

Week	Topic
1	Applications of MEMS in Biology and Medicine
2	Fundamentals of microfabrication technologies for biomedical microsystems
3	Working principles of pressure sensors
4	Pressure microsensors for clinical applications
5	Principles of microscale fluid flows
6	Microfluidic systems: valves, pumps and mixers
7	Biochips and Lab-on-a-Chip (LOC) devices
8	Chemical sensors and biosensors
9	Biocompatibility
	Microsystems for cell studies
10	Packaging of biomedical microsystems

relevant biological and medical topics. For students that desire a more in-depth treatment of these topics, we offer a graduate course *ECES707: Biomedical MEMS* in the following quarter, which covers the relevant biomedical and chemistry topics in much more detail.

The course used an existing MEMS textbook[2] written for advanced undergraduate or entry-level graduate engineering audience. The textbook was selected due to its coverage of microsystem design topics as well as MEMS fundaments (e.g., fabrication, mechanics, thermodynamics, etc.). At the present time, there is no upper-level undergraduate BioMEMS textbook. The teaching style also included the use of PowerPoint presentations and a whiteboard. To supplement these materials, students were given journal articles to read related to the topics covered in class. The strategy here was to expose students to the state-of-the-art and give them a flavor of what happens in the research environment. The first article was a review, but by the end of the course students were reading current research articles. Papers used in the most recent offering of the course, as well as comments on their selection, are listed in Table 2.

This year, students were evaluated through six homework assignments, six 10-min pop quizzes, a midterm exam, and a comprehensive final exam; graduate students also wrote a paper. For graduate students, homework assignments comprised 20% of the final grade, with the midterm and final exam weighing 25% and 30% respectively. The paper was worth 15%. Since undergraduate students did not have a paper, homework and two exams each weighed an additional 5% (i.e., 25% homework, 30% midterm, 35% final). Quizzes were worth 5% for both student groups. An additional 5% were allocated to class participation.

Twenty two students, 10 undergraduate and 12 graduate, enrolled in the course. All three programs within our department were represented, namely electrical engineering, computer engineering, and computer science. The class had four female students (~18%). By comparison,

Table 2. List of supplemental journal paper used in the course.

Paper	Topic	Comments
Voldman *et al.*[3]	Applications of MEMS in Biology and Medicine	A good stating point for students; provides a brief methodical review of microfabrication technologies and their applications in molecular biology, cell biology, and biosensors; discusses advantages and *disadvantages* of using microfabrication
Melvas *et al.*[4]	Pressure microsensors for biomedical applications	An example of conventional MEMS technologies applied to medicine—an ultraminiature pressure sensor specifically designed for intravascular blood pressure measurements
Stroock *et al.*[5]	Microfluidics	An example of a microfluidic mixer that can be applied to mixing bioreagents in lab-on-a-chip systems
Olsson *et al.*[6]	Microfluidic systems	A valvless diffuser pump for microfluidic pumping that can be used in lab-on-a-chip systems
Lee *et al.*[7]	Biochips and Lab-on-a-Chip (LOC) devices	An example of a lab-on-a-chip device—plastic biochip for analysis of DNA
Tan *et al.*[8]	Microsystems for cell studies	Discusses micro contact printing and polymer casting, and illustrates how MEMS can be used to study cell adhesion and traction forces

in the last year's offering, 34 students took the course: 8 graduate and 26 undergraduate, of which 4 were female students (~12%).

Addressing Student Feedback

On the last day of class, in last year offering, students were provided with an anonymous course evaluation that asked a number of open ended questions. As discussed in our report last year,[1] the overall student reaction to the course was generally favorable although mixed. Below, we summarize student feedback and discuss how it was addressed in this year's course offering.

Most of the students were enthusiastic about reading the supplemental research articles as they provided a real world perspective. This was a new experience for most of the students, and was quite different from what they have come to expect from other senior /first-year graduate level courses. Thus, this aspect of the course was retained without modification. However, several research articles from last year were replaced with articles we felt were more relevant to the course lecture material.

Many students wanted to see more biology and chemistry, including more in-depth coverage of biological applications. Some students felt that too much time was dedicated to the discussion of microfluidics, and that shortening the topic would allow for more discussion of biology and chemistry. However, we feel that the coverage of microfluidics was appropriate, given its importance in operation of biochips and LOCs which are an integral part of many Biomedical Microsystems. Nevertheless, a research article dealing with plastic microfluidic biochips for DNA analysis was added to supplement the lectures and to further illustrate the importance of microfluidics in BioMEMS.

Graduate and undergraduate students had different opinions of the breadth and depth of the course. Graduate students felt that the course did not cover the topics in enough depth. Most of them were enthusiastic about the assigned research articles and thought there should have been more. At the same time, undergraduate students felt overwhelmed by the amount of the material covered in the course. They felt that the pace of the course was too fast for covering this much new material. We believe the reason for this perception stems mainly from the interdisciplinary nature of the course. The emerging field of Biomedical Microsystems or BioMEMS is a synthesis of prior knowledge and therefore requires familiarity with other fields. However, complete mastery of those fields is not reasonable. Ideally, other introductory courses in biology and mechanics would cover the fundaments, which would permit this course to cover either more material or perhaps more advanced topics in greater depth.

To make this year's course more challenging, graduate students were required to write a 6 page review paper on a topic relevant to biomedical microsystems and selected in consultation with the instructor. Paper topics spanned a variety of biomedical microsystems, including biosensors, microfluidic systems, lab-on-a-chip devices, drug delivery devices, and surgical microinstrumentaion. Students were required to use a minimum of 4 independent journal references (which they submitted with the paper) and had to follow the IEEE format for conference proceedings[9]. The papers were evaluated based on six categories: organization and clarity, background, methods, literature search, results, appropriate detail, and layout and formatting.

To ensure that the undergraduate students were not overwhelmed by the material and to evaluate course pace, we introduced 10-min long pop quizzes in the beginning of some lectures. These quizzes were used to test understanding of concepts presented and discussed in class. Based on the quiz results, topics identified as challenging were revisited during lectures. Representative questions from quizzes are given below.

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1. *Draw two cross-sectional diagrams, one for positive photoresist and one for negative photoresist, following UV exposure through a rectangular mask and development.*

2. *On the unlabeled axes below, draw a temperature curve on the left and a pressure curve on the right during a typical embossing process. Label axes properly.*

3. *On the unlabeled axes below, draw stress-strain curves you might expect from PDMS polymer (mostly silicone rubber) and from alumina (ceramic). Label axes properly. Indicate: (a) Young's Modulus, (b) Toughness, (c) Total stress.*

4. *List four actuation methods that you can use for actuating a membrane pump in a BioMEMS device.*

5. *What is a reference electrode? List two materials commonly used as reference electrodes in electrochemical sensors.*

Course Evaluations

Important questions we wanted to answer were: *How does student performance this year compare with the last year? Did quizzes have an effect on student performance?* To attempt to answer these questions, we examined student grades and on the last day of class asked students to respond to a number of open ended questions in an anonymous course evaluation. Nineteen students responded to this informal qulitative survey. Responses to key questions are summarized below.

In response to the question, "Where the objectives of the course met?" students responded:

- *I believe the goals of the course were accomplished. We were introduced to various biomedical microsystems and developed an understating of their applications in biology and medicine*
- *Yes, we gained a clear insight into the applications of MEMS in biology and medicine*
- *Yes, but quite a lot of content in a short amount of time*

To the question, "What was the best aspect of the course?" students responded:

- *Quizzes and homework made the course more straight-forward*
- *Reading research articles provided a new prospective on and more in-depth understanding of fabrication methods*
- *The course was organized well and easy to follow*
- *Very interesting material; I took the course to see if it was something I would like to pursue; I enjoyed the topics covered and plan on taking more*
- *I gained an understating of the developing technology; good exposure to new technologies in MEMS*

To the question, "What would you suggest improving?" students responded:

- *Too much time was spent discussing the basics of engineering mechanics before learning about their applications*
- *More details in biological area*
- *Reading more articles appropriate to the progress of the course*
- *Too much time was spent on fundamentals of fabrication; more emphasis should be placed on applications*
- *Microfluidics description – I had never seen any fluid dynamics and the textbook was not very helpful*

Surveys revealed that the overall student reaction to the course, similar to that of the last year, was generally favorable, although mixed. As last year, the majority of students felt that the goals of the course were met. The use of research articles to supplement lecture materials worked very well once again. Undergraduate students were enthusiastic about reading research articles, as they provide a real word prospective and were quite different from what they used to seeing in other courses. They felt that the number of articles was quite appropriate. Graduate students also remained enthusiastic about the assigned research articles. However, even after having to research a paper topic and identify a minimum of 4 appropriate journal papers, they still thought there should have been more emphasis on the use of journal articles in the course. This was similar to comment from graduate students last year.

This year more emphasis was placed on biology and less on microfluidics. Nevertheless, some students still wanted to see more biology and chemistry and less microfluidics. A number of students, particularly undergraduates, felt that the textbook did not adequately describe the fluid mechanics needed to understand the microfluidic concepts discussed in class. Unfortunately, at the present time, there is no upper-level undergraduate BioMEMS textbook; thus this concern will need to be addressed with supplemental lecture materials in the next iteration of the course.

Students generally felt that the quizzes and homework assignments helped them learn the material. However, the graduate students performed on average 12% better on quizzes than the undergraduates. The overall weighted average score in this year's course was approximately 81%, a 7% improvement over the last year. We believe that this improvement is due to engaging students more in class, often through discussions following pop quizzes. It is interesting to note that while the undergraduate performance was only marginally improved from ~72% last year to ~73% this year, graduate student performance increased from ~82% last year to ~87% this year. A review of class records suggests that one factor contributing to the lower average score of the undergraduate students this year was perhaps due to a greater number of missed quizzes and homework assignments as compared to graduate students this year and also to the class population last year. It also appears that the introduction of quizzes did not seem to help the undergraduate students as much as it did for the graduate students. It appears that graduate students performed better when they were challenged more.

Conclusions

Overall, we feel that the course has been improved compared to the previous offering. In the next iteration, we plan to continue supplementing lecture materials with research articles, which will be reviewed and updated with more recent publications as necessary. A potential idea for the next offering of this course is to assign graduate students two research articles for every one articles assigned to undergraduates, which we expect will put more emphasis on current journal articles. Quizzes, while not having the effect we expect, led to more engaging discussions in the class. We plan to continue to use quizzes in the next iteration of the course. Furthermore, we will continue to revise and update our lecture materials and search for a textbook that is a better match to our course needs.

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