AC 2012-4090: INTRODUCTION OF CNC MILLING TO FIRST-YEAR ENGINEERING STUDENTS WITH INTERESTS IN NANOTECHNOLOGY AND MICROFLUIDICS

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Abstract

An early introduction to various prototyping and production technologies is important to the education of engineering students [1]. As such, the skills learned in early engineering classes build a strong foundation for students that maintain their relevancy in job markets and provide valuable knowledge that can be applied in upper-level engineering classes. As a result, many universities have cornerstone design projects for their first-year students, allowing them to get hands-on experience throughout the design process [2].

CNC milling is a widespread technology with many useful applications in both industry and research. Typically, however, this equipment is not introduced to all engineering students, and even then, only introduced in higher-level classes. The Ohio State University has created a first-year engineering course that is focused towards students interested in nanotechnology and microfluidics, utilizing CNC milling for manufacturing [3].

At the aggregate level, students had a positive reaction to their CNC milling experience, regardless of declared major. Additionally, at the conclusion of the course, students presented their designs and manufacturing techniques to faculty and industry professionals.

Introduction

During the first-year of engineering education, many institutions have broad courses covering basic engineering concepts for all first-year students. This method allows students to diversify their experiences in engineering, providing basic experience in all types of engineering. After the first year, however, students concentrate on topics unique to their majors, and learning about other engineering types is difficult without pursuing a minor or taking unnecessary classes not required for their major program. As such, it is important to introduce concepts to first-year students that, while not necessarily being a part of their major, can be useful in their further studies and careers.

While many internships and early job positions are educational for students, a basic prior knowledge of a subject can greatly help retention and understanding when acquiring new skills in real-world positions [4]. A class that offers a wide diversity of experience, even at the basic level, can help students be more confident in their future work and more willing to learn and apply their prior knowledge to new applications [5].

Computer automated machining such as CNC milling, is a valuable skill for many engineers, and currently, education in this subject is not widespread. Many engineering programs do not teach methods for automated machining to younger students, and some engineering disciplines may not learn these skills at all [6]. While prototyping methods are now a common part of the design process, few students are able to confidently create a machined physical model at the end of their college career [7]. It is important that students of all engineering disciplines have knowledge of milling methods so that they may utilize the technology in their careers [8].

Additionally, CNC milling has become a viable resource in many industries. With advancements in technology, the price of materials and CNC machines are no longer prohibitive and provide a valuable resource for quick, custom production and prototyping. While an intimate knowledge of machining logic may not be necessary, a basic knowledge can help to facilitate communications between different types of engineers spread throughout an organization [6]. This not only facilitates faster communication, but also allows engineers to realize the limitations and full capability of such technologies.

This paper discusses a class provided at The Ohio State University to first-year, honors engineering students with interests in nanotechnology and microfluidics. During the course, students are introduced to research methods as well as topics typically reserved for higher-level engineering classes. One such topic includes CNC milling, which is discussed in depth. Students' feedback about the class was monitored and their proficiency with milling techniques was measured using several methods and showed that the students were able to understand and apply the knowledge in projects throughout the course.

Problem Formulation and Initial Conditions

The Ohio State University created a course that could effectively teach students the subjects of microfluidics and nanotechnology. The course also included concepts that are traditionally taught in higher-level undergraduate courses, specifically computational fluid dynamics and design and manufacturing methods. The new course had to account for students' backgrounds in engineering, and relies heavily on two previous courses taught during the first-year engineering program; the course is part of a three-quarter series entitled Fundamentals of Engineering for Honors.

For this class, it was assumed that students had not previously used any type of CNC mill and had no prior knowledge of manufacturing methods. These assumptions meant that the class had to successfully communicate both the benefits and limitations of several different manufacturing processes, such as chemical vapor deposition, stereo lithography, and CNC milling.

The course, being relatively new, has changed its teaching methods in an attempt to find the most useful and effective ways to introduce these ideas to students, and currently does so through hands-on teaching methods, to maximize student interest and knowledge retention [9]. That said, the course remains dynamic in its education methods in an effort to keep up with present technologies and teaching practices, and is presented here as it was taught in the spring of 2010.

Class Description

The course, the third part of a three-part, fundamentals of engineering series, was designed to introduce project design to first-year engineering students. Students were given three different options as to the design project class they could take—a robotics and programming class, an infrastructure design class or a class on the principles of microfluidics and nanotechnology [10]. All of the design projects meet the same requirements for pre-requisites, and are meant to teach students principals of design, research, project planning, and teamwork. The latter two courses are relatively newer, and therefore smaller classes. Students were able to select freely which course they would like to participate in.

Many of the students who took the nanotechnology and microfluidics course were Biomedical or Chemical Engineering pre-majors. All were honors students and had previously taken a course in mechanical drafting and drawing, as well as a course in computer programming using C++ and MATLAB. Students were placed in teams of four by matching groups based on self-supplied characteristics, such as leadership ability and confidence when using solid modeling programs.

The class consisted of two parts: a hands-on microfluidics part and a theoretical nanotechnology part. During the microfluidics section of the course, students learn basic principles of fluid flow in micro-tubes and were asked to design an experiment that investigates the relationship between the surface pattern of a molded polydimethelsiloxane (PDMS) chip and the adhesion of yeast cells to the surface of a micro-channel. The nanotechnology part of the course was largely theoretical, and asked students to investigate possible methods of drug delivery to cells using electroporation. Both of these projects offered a research-oriented approach to design, with students reading scholarly articles on relevant subject matter, and performing analysis on the feasibility and efficacy of the designs.

In the microfluidics section of the course, students were asked to design small two-inch-diameter chips to be used in their experiments. The students then used milling techniques to create the chips as well as acrylic chip holders using a compact computer numerical controlled mill (CNC). After designing the chip, students used microfluidics concepts taught earlier in the course to model the flow of fluid in the chip in ANSYS Workbench.

The nanotechnology portion asked students to design an effective method of drug delivery using electroporation. This required students to research the methods used to deliver the medicine as well as the equipment that would be fabricated to implement the drug-delivery scheme. Students had to design their own equipment and price out the cost of each unit.

During their research students were told to keep records of all their work. At the end of the course, students turned in all documentation created (in the form of several-inch-thick binders) as well as bound reports of their research. Students were encouraged to use the reports when applying to internships as a way to show the research they had performed and evidence of their recordkeeping and writing skills.

The entire course concluded with two final presentations of the student groups, with smaller, in-class presentations throughout the class to improve students' public speaking skills. The final presentations consisted of a poster presentation as well as a more formal presentation to a group of peers. The poster presentation allowed the student to present their data collected from the microfluidics portion of the course to members of faculty and industry. During the presentation, students were queried by judges about their experiences, as well as any questions about the experiment the judges may have had. The second presentation had student groups presenting their ideas from the nanotechnology portion of the course to members of faculty who are actively researching in fields related to the students work.

After the presentations were completed, students were awarded scores, which then determined the teams to receive scholarships for their work. Also, written documentation was submitted along with reports from earlier mentioned robotics and infrastructure courses to compete for a best documentation scholarship.

Student Design of Wafers and Holders

For the microfluidics section of the class, students designed their own acrylic wafers (a negative image used to mold the actual PDMS chip, Figure 1) and chip holders (Figure 2) to be used during their experiments, which were then created using a compact CNC machine. The design of these parts was split into three parts to fully implement the design process.

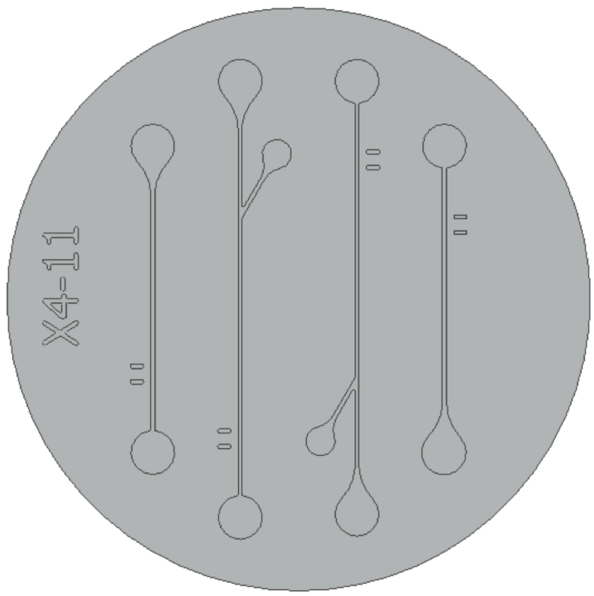

Figure 1: A chip molded from a student-designed wafer to be used in the microfluidics portion of the class.

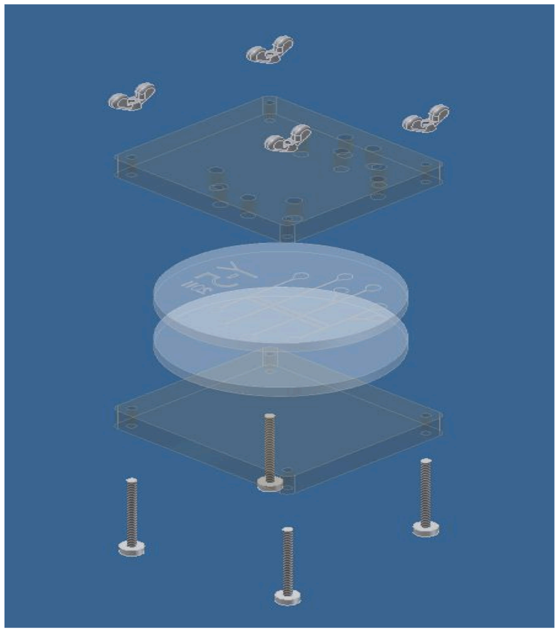

Figure 2: An exploded view of a student designed chip and holder assembly.

First, students had interaction with a basic chip design during the first portion of the class. The basic chip design used two different lengths of straight channels and used a simple chip holder. Students were told that they would be designing their own chips and chip holders to be used in experiments and were encouraged to add their own ideas for general improvement to the basic designs provided to them. Student groups were then asked to brainstorm and submit a list of parameters for their design, such as channel dimensions, as well as reasons for design changes. Each student was also asked to submit one sketch for each of the two different types of wafers, as well as a sketch for the chip holder bottom and chip holder top. A member of the teaching staff provided feedback on the sketches and ideas.

Students were then asked to meet back in their groups and refine their ideas further, and model one idea per group in Autodesk's Inventor software. A member of the teaching staff provided feedback on the models. One important element of this feedback was to ensure that milling of the chips and holders was possible. During this phase of design students were provided with a list of considerations that should be observed when designing their chips as well as reasons for these limitations. Minimum radii of filets, depth of cuts, and minimum thickness between edges were important limitations provided to students.

To complete the design process, students were asked to refine their models based on instructor feedback. Students then provided a fully dimensioned final model of their chip wafer and chip holder to be submitted for approval. Upon receipt of approval students were ready to begin the process of converting their models to CNC milling instructions (G-code).

Student Interaction with CNC Milling Concepts and Machines

During a previous course, students were introduced to the Autodesk Inventor solid modeling program. This course introduced another software package, Dassault Système's SolidWorks, which used the FeatureWorks software package to create the code needed to control the CNC machine. Students were told to model the chip wafers, as well as the chip holder bottoms and tops in the more familiar Inventor software package and then export the shape to a common solid modeling format, such as STEP or IGES. Students then followed procedures (with teaching assistants' help) to convert their designs. During the process, students selected the stock used to make their parts and were made aware of the affect of speeds and feeds on the milling of acrylic. Students were then able to "play" the milling process, which provided an estimated amount of time needed to mill their designs.

Due to time constraints, student groups were not all able to mill their own chip. Sometimes, multiple groups would complete the process of loading the G-code and starting the mill. This included attaching the appropriate cutter, zeroing the cutter, and beginning the milling program. Students were then able to watch all or part of the milling process, allowing them to observe the real life speeds and feeds used to mill the acrylic.

Applying Knowledge to the Nanotechnology Device Design

A crucial part of the nanotechnology section of the course is the design of a device to implement the researched medicine delivery method (Figure 3). These devices are generally complex acrylic blocks that utilize membrane inserts of different materials, as well as metal electrodes. Students are asked to do such things as identify the viability of implementation, such as cost per unit and ease of use to a technician. In order to estimate cost, students are asked to find the estimated cost of stock needed for their product as well as the cost of milling the acrylic for their device.

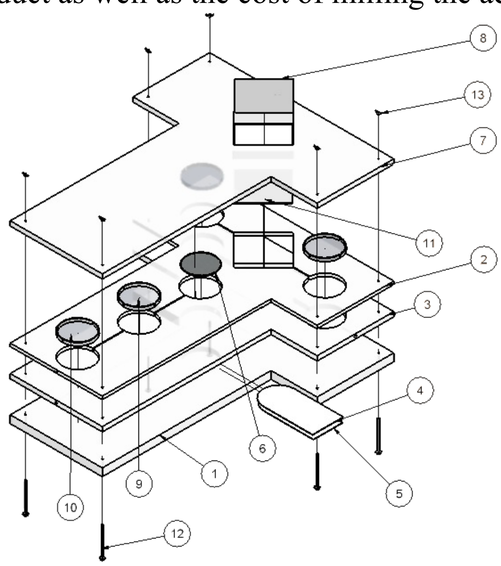

Figure 3: A student-group-designed device to deliver medicine to cells. Part of the Nanotechnology section of the course.

Students were asked to consider the ease of production for their devices, specifically the ability to use a CNC mill to cut the desired features. Many students initially created designs that were too complex to efficiently mill, and were asked if they could find ways to break up their design into different parts, so that milling would be a simpler and more inexpensive production technique.

Also considered was the price per device, which is directly affected by the milling-time required per device. Students were encouraged to contact companies to determine the price of milling per unit time. Students were then asked to estimate the time needed to mill; some students voluntarily created G-code for their devices, using the procedures from the microfluidics portion of the course, so that they could more accurately determine the milling-time per device.

Discussion

Feedback about the processes used in the class was solicited from the students by online, anonymous journal entries, as well as end of the term course evaluations. Student reviews of the course are mostly positive, with many citing the introduction of higher-level subject matter as a very valuable part of the course. Some extracts from student evaluations include:

> "I really enjoyed this class and felt that it was a great way to prepare for future classes/work."
> "I learned about a lot of really tough stuff and had a good time doing it."
> "I really liked the inventor designs of the microfluidics chip [sic]"
> "Learning the software will be in my opinion the most beneficial."
> "…[the class] gives me experience with the process and completion of research projects."

Many students took great pride in the work they had done and the chips and chip holders that they had made. For their micro-fluidics presentations, groups competed in a poster competition and were encouraged to bring their completed chips to the presentation and explain them to the judges. At the end of the class, there was some debate between students as to who got to keep the completed chip and holder, as well as the documentation that accompanies each of their presentations. This pride in their work indicates that the students had a sense of accomplishment, and that their experiments meant more to them than just another assignment [11].

Additionally, students were asked to evaluate the course at the end of the quarter, specifically evaluating any improvement the course may have had on their technical skills. These skills were evaluated on a five-point Likert-type scale, with '1' being the lowest proficiency and '5' being the highest proficiency. 88.37% of the students enrolled in the course ranked their abilities in managing and planning a research project as a '4' or a '5'. Additionally, at the completion of the course, 95.0% of students ranked their analytical and problem solving skills as a '4' or a '5'. The raw data is included below.

Table 1: Student Responses to a Likert-Type Analysis of Skill Sets

	1	2	3	4	5
Research Skills	0	0	5	22	16
Analytical Skills	0	1	2	20	20

Student grades on the design portion were typically good, with most students doing well on the drawing (98% average) and final design (97%) assignments and slightly worse on the initial brainstorming project (82%). The grades do indicate teams having a better performance near the end of the design assignments, with only four groups having decreasing grades out of the total 12 groups.

At the end of the course, students presented to members of industry and faculty performing similar research. The average score from the judges was 79 percent for the presentations, with performance being judged on professionalism, content, and background knowledge. Also, for the nanotechnology panel presentation the average score was 84 percent. Both these scores demonstrate the high skill level the students acquired in the pertinent subject matter.

In addition to the research experience attained by the students, it is important to highlight that the student work with CNC milling was a unique experience to students in the nanotechnology and microfluidics course. Typically at the Ohio State University, CNC milling is reserved for higher-level students, with many using the technology for the first time in senior capstone courses. Also, classes that do work with these mills are not widely available to students in Chemical and Biomedical Engineering majors.

Knowledge about CNC milling and its limitations is an important skill that clearly has relevance in engineering fields that are not traditionally associated with the process. Nanotechnology and microfluidics are just small subsets of Chemical and Biomedical Engineering, and there are many other uses for milling skills. An example of this would be for prototyping design with artificial limbs. In addition, students who do decide to go into a major that uses the technology, such as Mechanical Engineering, are able to gain a base knowledge that can be applied in further classes.

Because this course is still in its early stages, retention and GPA data for former students is not available.

Conclusion

This course served many purposes to first-year students, introducing new concepts that sometimes would not be covered until higher-level classes, or even not at all[8]. While CNC milling is not the main focus of the class, it is a crucial part that provides valuable knowledge to the students. This course was able to successfully introduce high-level concepts on a basic level, such as milling and computational fluid dynamics to students; they can extrapolate the concepts to future applications and even try to apply the knowledge in research or industry. Students overall showed a positive reaction to the introduction of milling skills, which included the basic concepts of creating G-code, as well as the benefits and limitations of such technologies. The students showed a positive interest and pride in their work, indicating that they have higher retention of the material[11]. This type of milling serves as a valuable resource in engineering for quickly producing custom models and prototypes, and its uses are not limited to Mechanical Engineering applications, which was shown by its use in this course.

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