AC 2010-2065: ENGINEERING DESIGN, CAD AND FABRICATION SKILLS WITHIN A BIOMEDICAL ENGINEERING CONTEXT

Eric Kennedy, Bucknell University

Donna Ebenstein, Bucknell University

Engineering Design, CAD and Fabrication Skills Within a Biomedical Engineering Context

Abstract
The challenge of exposing biomedical engineering (BME) students to the broad array of core engineering and biology topics often makes it difficult to adequately address supporting skills such as computer-aided design (CAD) and fabrication in the undergraduate curriculum. This paper will present a six-week module from a course developed to introduce students to hands-on skills that could be important for BME students in design and their future careers.

The BME "Cube of Knowledge" is a design and prototyping project where six design teams work together to create a six-sided cube. Each team first develops a CAD model, rapid prototype, and engineering drawings for one side of the six-sided cube. After the creation of engineering drawings, each team fabricates their individual side of the cube with a conventional milling machine based on the engineering drawings. After each team has manufactured their own part, the six individual parts are assembled in class. A successful design and manufacturing experience would predicate that the six parts, or "sides," combine to create an assembly in the shape of a cube, where each of the six sides are fabricated from a different material commonly used in biomedical engineering. Most materials used are biocompatible polymers, but metals such as stainless steel and aluminum have also been used.

Each step of this design and prototyping project has a different emphasis. For example, in the initial CAD model and rapid prototyping portion, students are required to use several advanced CAD functions to create geometries that would be difficult or impossible to fabricate using conventional machine shop tools. The CAD models are then simplified for fabrication using a milling machine, with the emphasis in the machine shop focusing on each student gaining hands-on experience machining the part.

Preliminary student assessment indicates that the students feel that designing, rapid prototyping, and physically producing the Cube of Knowledge was both a valuable and enjoyable experience. The vast majority of students agree that the project experience will be valuable for senior design and their future engineering careers. Additionally, they indicated that they would like to see the module expanded to include a larger variety of fabrication techniques and more time for basic skill development.

Introduction
Given the broad spectrum of topics that must be addressed in an undergraduate biomedical engineering (BME) curriculum it is difficult to provide adequate exposure to students in design and manufacturing technology such as computer-aided design (CAD) and conventional machining [1]. These skills are vital for engineers to communicate design ideas, and a basic understanding of manufacturing technology helps enable students to consider how a design on paper might be turned into a physical prototype. Faculty observations and student and alumni feedback have indicated that these skills are vital for success in classroom design projects such as senior design, as well as for careers in industry [2].

Within the biomedical engineering curriculum at Bucknell University, a fabrication and experimental design course is integrated into a four course design sequence where two courses comprise the senior capstone experience and two courses teach supplementary material. The intent of the sequence is to provide experience with a variety of skills that are valuable for both senior design projects and in BME careers after graduation. As designed, the Fabrication and Experimental Design course is not a full-credit course, meeting only two days a week for one-hour sessions, with several lab sessions (approximately 2 hours long) scheduled outside of normal classroom hours. Included among the skills introduced in the course are the use of CAD software, an introduction to rapid prototyping machines and a hands-on introduction to the machining tools of the College of Engineering's machine shop. These skills are taught for the first half of the semester, with the second half of the semester currently devoted to other biolaboratory skills such as cell culturing and biocompatibility experiments, along with a review of biostatistics.

During the initial course offerings in the fall of 2006 and 2007, students were taught the CAD software program SolidWorks, and were exposed to manufacturing and machining technology by demonstrations given by the staff in the College of Engineering's machine shop. Faculty observation as well as student feedback indicated that more hands-on exposure to machining skills would be beneficial. Therefore, a project-based design and fabrication experience was introduced to the course in the fall of 2008 and further enhanced in the fall of 2009 to marry the CAD and fabrication portions of the course. This project allowed students an opportunity to follow a process from design conception through prototyping and offer a hands-on opportunity for final production. The general idea for the project, colloquially referred to as the "Cube of Knowledge" was to provide a context to teach several aspects of engineering design, CAD and fabrication skills with a project that involved the whole class, but afforded individual students the chance to run the machines and develop personal experience with the skills, technology, and effort that is required to produce a precisely machined part.

Project Overview

The Cube of Knowledge project consists of a very simple overall design made up of six rectangular pieces that are assembled to create an equilateral cube. The rectangular pieces are affixed via two different specified types of screws. During the project, the class functions as six design teams of approximately 2-4 students, where each team is responsible for final design details on a single side of the cube. Each team designs a different side of a cube, which will later be assembled to form a complete cube that will be fastened together by screws. Each side of the cube is made from a different material relevant to the biomedical engineering field which exposes the class to a wide variety of materials that can be used in the fabrication process and in machining operations. Materials that have been used include: acetal (Delrin®), chlorinated polyvinyl chloride (CPVC), acrylonitrile butadiene styrene (ABS), polycarbonate, acrylic, polypropylene (PP), aluminum, and stainless steel. An example SolidWorks model and a photo of a final product are shown in Figure 1.

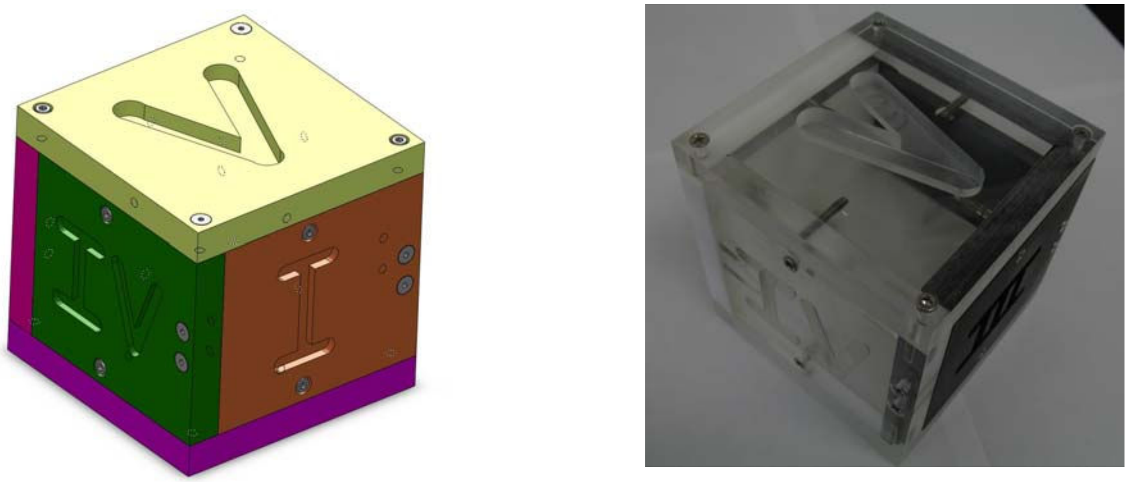

Figure 1: Examples of the BME Cube of Knowledge. The photo on the left shows a final SolidWorks assembly file that has been created by one of the design teams. Each team must make a full assembly file using other teams' models and include the appropriate hardware. The photo on the right shows the final assembled model. Note the sides shown "IV" and "V" are made out of polycarbonate and acrylic, respectively.

The overall purpose of this project is to expose students to the manufacturing process for a small assembly, including part design, rapid prototyping, engineering drawings, and hands-on fabrication. The first step in this process is to create a model of each part in a CAD program and bring the parts into an assembly to check if all parts fit together properly. The second step is to create a rapid prototype of the device, building all parts separately and then assembling the device and making sure that all the parts fit together properly. Finally, the device is fabricated using conventional machine shop tools. Specifically in this project, we focus on a manual milling machine, and give an overview on other types of machines.

At the conclusion of the project, each team must produce a memo that is distributed to the other members of the class that details key attributes of their material used for the Cube of Knowledge. Information in this memo includes documentation of material properties, example biomedical applications, and detailed discussions of biocompatibility issues and sterilization methods for the material used.

The complete project from start to finish takes approximately 7-8 weeks starting from instruction in SolidWorks to the final project deliverable:

- SolidWorks Tutorials and Instruction (2 weeks)
- Rapid Prototyping (1.5 weeks)
- Engineering Drawings (1.5 weeks)
- Fabrication and Material Memo (2-3 weeks).

Project Component Descriptions

This section of the paper will provide more detail for each portion of the project, including a description of student assignments throughout the Cube of Knowledge project.

1. Learning SolidWorks

The CAD package used in this course and throughout the design curriculum at our university is SolidWorks (current version 2008 SP3.1). Students are first exposed to SolidWorks through this course within our curriculum. Due to the quality of the tutorials within the program, we have found that our preferred way to initially introduce students to the concept of 3D modeling is to assign the introductory SolidWorks tutorials to be completed outside of class. These tutorials are:

- Lesson 1 – Parts,
- Lesson 2 – Assemblies, and
- Lesson 3 – Drawings.

After the students complete the tutorials to familiarize themselves with the program, we then review and discuss the software and functions in class. One of the main focuses of these discussions is on troubleshooting skills and how to make corrections to a model. This is a topic that is difficult to teach via tutorial and we have found that students appreciate the troubleshooting tips particularly after working on the tutorials and encountering inadvertent mistakes in their own modeling.

A second tutorial assignment is distributed after the in-class SolidWorks discussion/demonstration session. The second set of tutorials focuses on advanced modeling features and capabilities. The tutorials in this session are:

- 30-Minute lesson,
- Lofts,
- Revolves and sweeps,
- Pattern features, and
- Advanced design.

2. Design for Prototype

Although teams are aware of this phase of the project as motivation for completing their advanced SolidWorks tutorials, this initial Cube of Knowledge assignment is distributed immediately after the SolidWorks tutorials are completed. The intent of the assignment for each design team is threefold:

- To force coordination between design teams to jointly determine attachment positions to ensure that all sides fit together appropriately,
- To use advanced SolidWorks tools and features to add decorative details to each team's side of the cube that takes full advantage of the capabilities of a rapid prototyping machine to produce complex 3D geometry, and
- To provide an introduction to rapid prototyping that will be used later to emphasize the difference in manufacturing capabilities between rapid prototyping and conventional machining.

Teams have specific constraints placed on their cube design. The overall size and relative position of each team's side of the cube is suggested by the course instructor, but specific details such as screw type, size, and placement are left to individual teams to work out within the constraint shown below. Specific requirements used in 2009 were as follows:

Requirements for Basic Cube Design:

- Each part MUST have at least 4 tapped (threaded) holes for screws
  - Screws fitting into these holes will be at least two each of a #6-32 socket head and a #6-32 flat head machine screw, both 7/8 inches long
- Each part MUST have at least 2 counterbored holes for recessing the #6-32 socket head cap screw heads, so that screws will be flush with the surface when screwed in
- Each part MUST have at least 2 countersunk holes for recessing the #6-32 flat head machine screws, so that screws will be flush with the surface when screwed in
- Each part MUST have a Roman Numeral (I, II, III, IV, V, VI) corresponding to their team number labeling the outer surface (large face) of their cube

Specific Requirements for Rapid Prototyped Cube Design:

- The minimum thickness of any feature should be 0.08"
- The maximum height that you should extrude any feature is 1.00" from the face of your cube side.
- The Roman Numeral (I, II, III, IV, V, VI) corresponding to their team number MUST be extruded out of the block face (as opposed to cut into the face)
- At least one decorative feature MUST include a curved surface
- At least one decorative feature MUST be patterned
- At least one decorative feature MUST be created using either a swept boss/base or a swept cut
- You may choose to etch your team member's names, etc on the back face.
- Your cube side MUST still be able to be assembled with the other sides into a cube

3. Rapid Prototype

After students have completed the initial "Rapid Prototype" design, they submit a basic drawing of their team's side cube with appropriate views and annotations labeling the outer dimensions, screw types, hole sizes and positions. Decorative features and the roman numeral on the design are not dimensioned. As instruction has not yet been given on appropriate drawing conventions, these drawings are mostly to provide practice using the drawing features learned in the tutorials, and provide a starting point for later drawings. They also force each team to confront the idea of creating a drawing without having a set of guidelines by which the parts should be dimensioned.

Additionally, each design team submits an electronic file of their part, exported to the appropriate file type for use in the rapid prototyping machine (in most cases this is a *.stl file). These files are then submitted to the rapid prototyping technician within the College of Engineering, and models of each team's side are then created. In our particular case, our rapid prototypes are made of ABS plastic using a fused deposition modeling process. Examples can be seen in Figure 2.

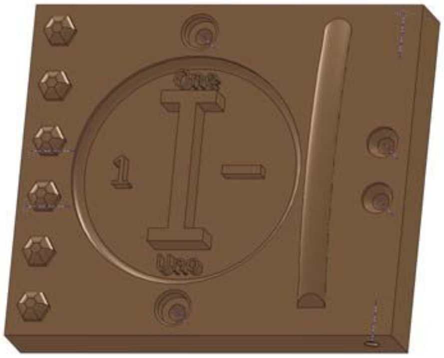

Figure 2: Examples of designs for the rapid prototyped side. The photo on the left shows a final SolidWorks file that has been created by one of the design teams (Team I). The photo on the right shows a completed ABS plastic rapid prototype part (Team VI).

When models are complete, they are distributed to each team for review and quickly assembled by the entire class to ensure that all screw holes line up and to verify that the parts fit together as planned. Class time is also devoted to providing biomedical applications and the benefits of rapid prototyping, including the speed at which parts of this complexity can be produced, as well as the ability to physically validate a design before machining a more time-consuming and costly physical model.

4. Tour of Machine Shop

While students are waiting for the rapid prototype machine to produce their parts, they are given a tour of the machine shop in small groups (limited to 8 students per tour). While the tour size can certainly be altered, we have found small sizes advantageous to allow every student to see particular machines up close, rather than from a 2nd or 3rd row vantage point. Additionally, there is an inherent safety issue present in the machine shop with larger groups.

The tours are given for the equivalent of one class duration (52 minutes). The purpose of the tours is to give a brief overview and introduction to all of the equipment, including drill presses, saws, conventional mills and lathes, computer numerical control (CNC) mills and lathes, injection molding and hand tools in the machine shop. Safety protocol is also discussed and students are given instructions which they must read prior to their fabrication appointment in the machine shop.

During the tours, examples of parts from previous biomedical engineering design projects are shown to link the equipment and its machining capabilities to a relevant example. The goal is to alleviate misconceptions about the machine shop primarily serving as a resource for mechanical and civil engineering design projects, and to introduce this facility to the students prior to their scheduled fabrication appointment in the machine shop. Second, we utilize the tour to provide an overview of equipment that students will not use during the fabrication portion of this project, so they are more aware of what is available to them for other design projects. Finally, because students have completed and submitted initial designs for rapid prototyping, some effort is made to highlight some design elements that would be difficult to produce using conventional (manual) machines.

5. Engineering Drawings

Students receive a minimum of two days of classroom instruction on proper engineering drawings. We teach fundamental drawing principles in accordance with ASME standard Y14.5 for geometric dimensioning and tolerancing [3]. While we cannot fully detail all aspects of proper engineering drawings, the goal is to expose students to several key principles of what constitutes a "good" engineering drawing. The following is a list of the dimensioning principles which are emphasized in the course, adapted from the ASME standard Y14.5 [3]. Each principle is followed by a brief explanation of why this concept was selected to be emphasized to the students.

> *"Each necessary dimension of an end product shall be shown. No more dimensions than those necessary for complete definition shall be given. The use of reference dimensions on a drawing should be minimized." [3]*

The most basic requirement of any drawing is that it fully and accurately defines the part shown on the page. We emphasize that duplicate dimensions should be avoided and may add confusion or clutter to the drawing.

> *"Dimensions shall be selected and arranged to suit the function and mating relationship of a part and shall not be subject to more than one interpretation." [3]*

It may appear that there are multiple ways to dimension, for example, a single hole's location on a given part. We emphasize to our students that the drawing should fully define a part while also expressing the important relationships between different features. If the height of the hole from the base is what is important, that is what should be dimensioned.

> *"Each dimension shall have a tolerance." [3]*

Given the time constraints within the class, we do not have time to go into complex tolerancing and analysis. However, we do introduce students to the basic concept of linear tolerances. At a basic level, we want our students to be able to successfully differentiate and communicate critical design features and dimensions from less critical dimensions. While these can be held to any desired value, we use a default tolerancing scheme of ±0.005 inches for critical dimensions and ±0.02 inches for non-critical dimensions.

> *"The drawing should define a part without specifying manufacturing methods." [3]*

The point we try to convey to our students is that in most scenarios, where a particular manufacturing method is <u>not</u> required, they should leave the manufacturing methods up to the machinist/technician who is building their part. They are encouraged to seek out expertise to ensure that their part is producible, but it may be unnecessarily restrictive to define exactly how something is to be made (unless required for functionality).

"Dimensions should be arranged to provide required information for optimum readability." [3]

We try to emphasize the importance of good dimensioning practice and that drawings, like writing, often require revision. Visual clarity on a drawing is just as important as fully and accurately defining a part.

Students perform a series of assignments related to engineering drawings after the conclusion of these lectures. In the assignments they are required to both produce engineering drawings of parts from a SolidWorks assembly, and to produce SolidWorks models from a vendor drawing.

6. Design for Fabrication

After the tour of the machine shop, and concurrent with their instruction and practice with engineering drawings, student teams must simplify their original model (produced by rapid prototyping) such that it can be produced in the machine shop. Essentially, all decorative features are removed from the design except for the required screw holes and the roman numeral identifier for each side.

Teams must prepare a full, accurate engineering drawing of this part (following the guidelines presented in class) prior to an appointment in the machine shop for hands-on fabrication. These drawings are reviewed and approved by the instructor prior to the machine shop appointment.

7. Fabricate in Machine Shop

Each student team (approximately 2-4 students) is then scheduled for a two-hour appointment with a manufacturing technician in the College of Engineering's machine shop. During this appointment, the technician details safety instructions with the students and works with them to fabricate the team's side of the Cube based off of the team's engineering drawing. Students are individually given opportunities to operate the milling machine, squaring the workpiece in the vice, performing cutting operations, drilling and tapping holes (Figure 3).

Figure 3: Students operating the conventional mill to produce their side of the Cube of Knowledge.

Students are expected to develop a basic understanding of the operations used to fabricate their part and to identify any particular benefits or issues associated with machining their assigned material. This information is also conveyed in the final written portion of the project assignment, the Material Memo described in Section 9.

8. Assemble Final Cube of Knowledge

After all student teams have rotated through their appointments in the machine shop and have produced their sides of the cube, the sides are assembled into the final Cube of Knowledge. If each part has been accurately produced, all tapped holes should align with thru-holes on adjacent sides and the thread depths should be appropriate. Students are given a chance to inspect the cube and observe any particular manufacturing errors or basic differences between different materials. Each group or team is asked to explain any challenges they faced in manufacturing their side of the Cube and discuss the source of any flaws in the final produced piece or the fit within the assembly. The discussion about the evolution of the project from concept to prototype to manufactured assembly also gives the students a sense of accomplishment and serves as an opportunity to reflect on what it took to bring this admittedly simple part to fruition.

9. Research and Write Material Memo

The final written portion of the project serves to disseminate information learned by each team regarding their particular assigned material to the class at-large. Each team must prepare a 2-3 page memo to both the instructor and their classmates to share pertinent information regarding the material they used to fabricate their side of the cube. Examples of what should be included are material properties, relative cost, manufacturability, and common uses of their material.

In addition to the previously mentioned details, the Material Memo is specifically designed to address biomedically relevant issues with regard to the specific material used. These issues include the identification of current biomedical uses for the material, including biocompatibility testing that must have been performed for those uses. Teams must also identify the sterilization methods commonly used for their material and indicate any potential safety concerns noted with regard to the specific material used.

To evaluate biocompatibility testing needs for specific applications, the students are asked to read the FDA guidance document titled “Use of International Standard ISO-10993, ‘Biological Evaluation of Medical Devices Part 1: Evaluation and Testing’” [4]. This FDA memo is designed to help researchers identify the biocompatibility tests that are needed for their device. The FDA document includes tables from ISO-10993-1 [5] that identify the necessary biocompatibility tests based on the anatomic location and duration of the device’s contact with the body. Students use the provided tables to identify all the biocompatibility tests that would have to be performed on their material for it to be approved for the biomedical applications they have identified.

These memos are collected and are collated by the course instructor to be redistributed as a set to each student at the end of the semester. The intent is that the collection of these memos may be of use for each student as a potential reference for capstone design projects and beyond. This research process provides students with knowledge of the resources that can be used to evaluate other materials in the future.

Student Assessment
At the conclusion of each semester that the Cube of Knowledge has been offered, students have been asked to fill out evaluations regarding their design and fabrication experience. After the Fall 2008 offering, the fabrication experience as a whole was evaluated using two broad questions. To further break down the effectiveness of different components of the project, 11 different questions were asked after the Fall 2009 offering. The questions are shown in Table 1 along with scores (using a Likert 5-point scale, with 5 = agrees strongly, 3 = neutral, and 1 = disagrees strongly).

Table 1: Summary of student evaluation questions regarding the Cube of Knowledge project.

Year	Supplemental Evaluation Question	Number of Students	Likert Score (Mean ± St. Dev.)
2008	I gained a greater understanding of concepts in this field.	17	4.6 ± 0.5
2008	This course has stimulated my interest in the field of fabrication and design.	17	4.5 ± 0.5
2009	My exposure to SolidWorks has given me a better understanding of the use of CAD to develop and communicate design ideas.	12	4.7 ± 0.5
2009	I have developed a better comprehension of engineering drawings through the Cube of Knowledge and drawing assignments.	12	4.5 ± 0.5
2009	The tour of the machine shop gave me a better understanding of the [machine shop] and the equipment available for project use.	12	3.8 ± 1.2
2009	The hands-on fabrication experience in the [machine shop] (machining my side of the cube) enhanced my knowledge about how physical parts are produced.	12	4.0 ± 1.3
2009	The experience gained from translating the Cube of Knowledge from a CAD model to a physical component will be valuable for senior design and/or my future engineering career.	12	4.3 ± 0.6
2009	Although each group only used one material, it was valuable to be exposed to the different materials used in the Cube of Knowledge by each group.	12	4.0 ± 0.6
2009	The biomaterials aspects of the material memo increased the biomedical relevance of the Cube of Knowledge project.	12	3.9 ± 0.7
2009	The information provided in the material memo from each group will be a valuable reference material/resource.	12	3.9 ± 0.9
2009	Designing, rapid prototyping, and physically producing a side of the Cube of Knowledge was a valuable experience.	12	4.6 ± 0.5
2009	Designing, rapid prototyping, and physically producing a side of the Cube of Knowledge was an enjoyable experience.	12	4.5 ± 0.7
2009	The level of complexity in the design of the Cube of Knowledge was appropriate for an introduction to design, engineering drawing, and fabrication experience.	12	4.3 ± 0.6

Preliminary student assessment indicates that students felt that the Cube of Knowledge project, as a whole, was both valuable (4.6) and enjoyable (4.5). The majority of students also agree that the project experience will be valuable for senior design and their future engineering careers (4.3). In addition, they clearly felt that they had gained a better understanding of the use of CAD (4.7) and engineering drawings (4.5) through this project and the related assignments. Some sample student comments are shown below:

> *"The content of this course was extremely valuable as an engineer. The [machine shop] experience was essential as was discussion of industry standards for drawings."*

"I learned a new skill in this course! Well actually more than one. SolidWorks machining and rapid prototyping are all important skills that engineers can take to the workforce."

While all components of the project received generally positive evaluations (≥ 3.8), the areas that show the largest room for improvement, based on student perceptions, appear to be the effectiveness of the tour of the machine shop and the materials memo. Additionally, the students indicated through written comments on their evaluations that they would like to see the module expanded to include a larger variety of fabrication techniques and have more time for basic skill development. These are aspects of the project sequence that can be improved upon in future iterations of the course. The machine shop tour, for example, could be enhanced by having a technician actually demonstrate each tool and its capabilities as the tour is conducted, which would also give the students more exposure to other fabrication techniques.

Discussion

Overall, we believe the Cube of Knowledge satisfies our goals of developing a hands-on, project-based introduction to design and fabrication skills. Overall, the students are engaged with the project and we believe that the project teaches students the capabilities of SolidWorks, including how to use tutorials to independently expand on their skills. We also believe that following a project from design inception to completion provides an excellent framework to focus on the concept of engineering drawings and that the hands-on experience in the machine shop teaches the students about the skill required to fabricate even a relatively "simple" part. However, we feel that there are several questions that may be appropriate to address:

1. Why was the basic cube selected over a more complex or biomedically relevant design?
2. Is it possible to scale this project up for larger classes?
3. What are potential variations on the current project?
4. What are the limitations of the current process?

In this brief discussion section, we will offer our interpretation of these questions.

1. Why was the basic cube selected over a more complex or biomedically relevant design?

While the final shape and individual pieces are seemingly very simple, the basic design was intentional for several reasons. First, we have found with regard to engineering drawings, fundamental dimensioning principles and practices are most clearly shown on a simple part. More complex examples are used in class and in other assignments, but the multiple iterations on a single side of the Cube of Knowledge show that students need time to master this relatively simple drawing prior to tackling a more difficult drawing.

Second, because this has been designed to be a hands-on project, it was necessary to find a balance between part complexity and the required production time for each design team. Even with the very simple design of the rectangular side, production time, including hands-on instruction for a two to four student team requires a full two to three hour session in the machine shop. Producing a more complex piece would have required significantly more instruction time per team, which would have dramatically affected the machine shop scheduling. At the outset, it was decided that the intent of the project was exposure to manufacturing methods, so that students would have an appreciation for the skill and effort required to produce a final part. We elected to focus on the conventional mill, given that its versatility and that it is relatively easy to learn. We did not have enough time to devote to teach our students how to set up and operate the machine on their own; however, they received enough fundamental exposure to potentially operate the machines (under direct supervision) for their senior design projects.

Third, it should be mentioned that a biomedically-based project was considered, but none were identified that enabled us to focus on the key concepts covered in this project. Therefore, despite its lack of obvious relevance, the cube shape was thought appropriate to introduce manufacturing and design concepts to biomedical engineers. In addition, the materials selected for use in this project were chosen due to their relevance to the BME field with more BME-relevant examples provided in class. In an effort to introduce the machinability of as many materials as possible, each side of the cube was a different, biomedically relevant material. These materials have also been used later in the same course as part of a cell culturing and biocompatibility experiment. We have tried, where appropriate to maintain sight of relevant biomedical issues such as biocompatibility and ISO 10993, sterilization, and safety risks, while teaching a skill set that reaches into topics more broadly associated with other engineering disciplines than biomedical engineering.

Finally, student evaluations indicated that they felt the project to be an appropriate level of complexity for this short introductory course (4.3). We have not observed an indication from students that they wish this project was more specifically geared towards a biomedically related problem, and for the reasons stated above, we believe that the simple geometric model of the cube allows us to maintain focus on the engineering drawing and manufacturing skill sets.

2. *Is it possible to scale this project up for larger classes?*

As presented here, we recommend a team size of 2-4 students, which would accommodate up to 24 students. Certainly this is somewhat arbitrary, and a slightly larger team may be possible, but larger sizes come at a cost of opportunity for individual students, in the CAD and in the fabrication stages of the project.

One option that would preserve the opportunities for individual students, while minimizing the strain on the machine shop would be to divide into two separate groups for all but the fabrication portion of the project. Each team could rapid prototype their design, and teams assigned to similar sides could combine to observe and participate in the conventional machining process.

It should be noted that perhaps the biggest challenge in this project is coordination with the machine shop staff for the individual fabrication appointments. At a minimum, it will require at least two hours of fabrication time to produce each side of the cube, for a total of 12 hours of fabrication for the entire assembly. This must be coordinated with student schedules and has shown to require anywhere from 2-4 weeks before all teams can be cycled through (depending on class schedules and technician availability). Even if a lab section were scheduled for the class, each team would require supervision for their initial machining experience, and many machine shops may not be equipped to handle large volumes of students at a time.

3. *What are potential variations on the current project?*

Certainly there are many other potential variations on this project. For example, the same project flow could be applied to more complex assemblies as long as the overall product could be broken down into independent subunits for each team. In addition, different cube designs could be created that involve other types of fasteners or interlocking sides.

We have currently operated with the same cubic shapes (and overall individual piece sizes) each semester. Screws were selected as the method of fixation to keep the complexity of the design component of the project relatively low, and because screws are such commonly used fasteners. Many students have informally commented on the value of observing how tapped holes are created in workpieces, as they have not previously had exposure to how a threaded hole was cut into material. We do give students the freedom to determine their own tapped- and thru-hole locations, and have varied the required numbers and types of screws each year to encourage unique designs.

4. *What are the limitations of the current process?*

Probably the greatest limitation of the current project is the focused emphasis on the milling machine as opposed to all other manufacturing technologies. The milling machine was selected because of its overall versatility and frequent use in producing machined parts. It is perhaps the easiest conventional machining tool to learn and arguably provides the best opportunity to get our students hands-on exposure given a limited window of time.

It would be desirable for students to gain experience with CNC and other conventional manufacturing technologies that are prevalently used today. We focus on the mill to give our students an appreciation for the process of machining, not to develop proficiency in all available technologies. We have attempted to address this shortcoming with focused tours of facilities and examples of parts produced with other machine shop tools and manufacturing methods, but students have indicated a desire for exposure to more of these technologies.

Conclusions

The Cube of Knowledge project provides a hands-on project-based introduction to design and fabrication skills for biomedical engineers by allowing the students to follow a project from inception to fabrication. The Cube provides students with experience in CAD, engineering drawings, rapid prototyping technology and conventional milling, while also exposing them to other fabrication techniques. The project also exposes students to a variety of materials used in the biomedical engineering field, as well as issues relating to manufacturability, material selection, and biocompatibility. We believe this design to drawing to fabrication experience is beneficial to BME students prior to their senior design experience and their future careers.

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