A Scalable Instructional Method to Introduce First-Year Engineering Students to Design and Manufacturing Processes by Coupling 3D Printing with CAD Assignments

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Abstract

Providing first-year engineering majors with an opportunity to experience engineering through a project-based design course has become an important curricular element in many engineering degree programs. An introductory engineering design course at The University of Maryland, College Park, requires students to work in multidisciplinary teams of eight to ten to design, build, and test an autonomous vehicle. For over a decade, computer-aided design (CAD) software has been introduced as a course requirement with the academic promise that learning this material will become useful when you become an engineer. To address this contextual mismatch, ten consumer-grade 3D printers have been added as a course enhancement to this course, (ENES100). This paper describes a scalable instructional method that has been developed to better link CAD assignments to modern manufacturing processes and details challenges that were overcome to effectively integrate 3D printing into the course in a way that strikes a balance between reliability, ease of use, and learning potential.

Introduction

This paper describes the implementation of consumer grade 3D printers in a first-year introduction to engineering design course, ENES100, at The University of Maryland, College Park. Providing first-year engineering majors with an opportunity to experience engineering through a project-based design course has become an important curricular element in many engineering degree programs\(^1\text{--}^5\). Additionally, many experts point to the benefits of rapid prototyping in the engineering design process\(^6\text{--}^{10}\). The introduction of inexpensive and functional 3D printing technologies into the marketplace has permitted the adoption of this technology by many colleges and universities\(^11\text{--}^{12}\). The addition of 3D printers to engineering design spaces provides students with an authentic, industry-like opportunity to rapidly realize product concepts. The inclusion of 3D printing technology appears particularly useful in first-year cornerstone and senior-year capstone design courses\(^13\text{--}^{17}\). The remainder of this paper describes an approach for introducing 3D printers in a large introduction to engineering design course and the best practices learned through this experience. The approach described may be useful to others who are considering adding 3D printers as a course enhancement in first-year engineering design courses that typically service a large number of students. The best practices suggested within this paper include details related to the setup, modification, and maintenance of 3D printing hardware and an instructional approach that permits a large number of students to gain first-hand experience working with 3D printers.
The addition of these printers occurred during the Fall 2014 semester. Over 600 students were enrolled in the course this semester. The purpose of this class is to teach first-year engineering students important technical skills and practices necessary for engineering design. The students have the opportunity to tackle a difficult design challenge that requires them to use these capabilities, including working with a team, preparing and giving presentations, working under a budget, and constructing a functional prototype that accomplishes a complex set of objectives and adheres to a set of design specifications\textsuperscript{18}. In order to complete the project, students learn the basics of mechanics, electronics, programming, and manufacturing. Learning these skills is accomplished through a blended learning class structure\textsuperscript{19}. The first half of the semester is mostly instruction based, addressing the technical content required for the project, while the second half of the course is mostly hands-on, to allow the students to complete the project. Students work in teams to develop, prototype, and assemble a working vehicle by applying the material taught in the first half of the semester. Introducing additive manufacturing is intended to aid in conveying these skills, particularly with manufacturing and design. The students learn more about manufacturing by experiencing the entire design life cycle, from initial plans to creating a physical part. The printers allow students to experience this entire process within a single semester. By allowing students to directly create the parts that they are modeling, they become more proficient at using the software for its intended purpose. Providing students with these skills in their first year makes it more likely that they will use them for their endeavors as students and later on in their engineering careers. It is additionally beneficial for students to add 3D printing to their skillset because the technology has become far more mainstream in recent years and companies are seeking talent. In a 2014 study conducted by PricewaterhouseCoopers\textsuperscript{20}, out of 108 companies who responded, 45.3% selected that one of the largest barriers to full-scale adoption of 3D printing technology was “lack of current expertise in our company to fully exploit the technology and difficulty in recruiting talent.”

For the Fall 2014 semester, a model of 3D printer was selected. We tested a group of the most promising consumer-grade 3D printers available in order to judge them on relevant parameters and select the highest performing printer for use in the course. Ten of these printers were purchased for student use in the ENES 100 labs. These printers were modified, and configured with a system designed to streamline their use. We created detailed instructional videos for students to learn the policy and operations involved in 3D printing, and posted them online. All tools and equipment necessary to operate the printers were provided to the students, who were able to access the printers and become proficient experientially\textsuperscript{21}. 3D printer use and instruction was incorporated into a modified CAD module to create a coherent pedagogical approach to permit a more thorough retention of CAD related material. To determine the effectiveness of the 3D printer course enhancement, feedback was collected through a print...
logging system and a survey given to both current students near the end of the semester and students from the Fall 2013 semester who did not have access to this technology.

The remainder of this paper details the approach taken and lessons learned implementing 3D printers into a first-year engineering design course. First, implementation details including specific tools, techniques and equipment used in the labs are provided. Next, the instructional approach developed to introduce the concepts and techniques linking CAD with 3D printing is presented. Preliminary results of this effort are then discussed by presenting (1) the print log data collected throughout the semester that provides an indication of the use and success rates associated with the printers and (2) data collected from a survey designed to determine the perceived effectiveness of the system and student response. Next, we discuss changes made following the Fall 2014 implementation semester in response to the usage and user response data. The paper concludes by addressing the notion of scalability of the system for others who may be interested in adopting a similar approach at their institution.

Implementation

Equipment

To ensure an effective and uncomplicated system, it was necessary to select an appropriate model of 3D printer for use in this course. We tested five promising models to judge print quality, ease of use, and reliability. The CubeX Trio, MakerBot Replicator 2, MakerBot 5th generation Replicator, LulzBot TAZ 4, and Ultimaker 2 printers were all tested. In order to judge print quality, we designed a 3D model to test many of the common categories of features that 3D printers have difficulty producing correctly. Each structure in the model is detailed in figure 1, and the actual model printed by the Replicator 2 is shown in figure 2. The thin wall test and Z thickness test consist of features that are slightly larger or smaller than the smallest bead of plastic the printer can produce. Examining these features reveals how the printer and its associated software handle designs that are beyond its normal capabilities. The dimensional accuracy test is a one centimeter cube that can be measured after the print is complete. The overhang test can be used to determine the maximum angle the machine can print with a clean bottom surface. The retraction test is a field of small features that require the printer to jump from one to the other quickly, and this area will have thin strings of plastic connecting each structure if some parameter related to filament retraction is substandard. The sharp edge tests show how the printer attempts to produce features that narrow to a zero-thickness edge. The constriction and curved surface test should be smooth on both the top and bottom, or it could indicate that the heating and cooling of the material is not controlled correctly, causing circular features to shrink and become rough. The spire test is the tallest feature, and each layer is very small. If adequate cooling is not available, the top of the spire will not solidify sufficiently while printing, and will twist and bend during the print. The bridge tests allow us to see if the printer
software recognizes bridges in the design and alters the toolpath to compensate. The hole tests can be checked for dimensional accuracy and smoothness, and the vertical wall test shows how accurately the printer tracks along the z axis, and will be tilted or uneven if there is any play in the x or y drive systems.

**Figure 1** - Detail Views of the 3D Printer “Obstacle Course” Design and Features

**Figure 2** - 3D Printer Obstacle Course, as Printed by the MakerBot Replicator 2
To test the ease of use of the printers, some outside data was required to control for our own familiarity with MakerBot software. Each software package was introduced for the first time to staff and friends, and their feedback was used to aid in the final decision. The reliability of the printers was determined by consistent use of all tested printers as frequently as possible, and the results were clear. In every test, The MakerBot Replicator 2 was found to be the best option under consideration. The print quality was better than any other printer tested, all users agreed that the MakerBot Desktop software was the easiest and most intuitive software, and the Replicator 2 was easily the most reliable printer throughout the trial period. This printer could also be easily maintained and upgraded. For these reasons, the Replicator 2 was chosen for use in the labs. Five of these printers were placed in each of the two labs to allow each team access to a dedicated printer during class hours. It is worth noting that this model of printer is no longer in production; the extensive details of the selection process are provided so that others can follow a similar systematic approach when selecting reliable and easy to use printers in the future.

Some modifications and improvements were made to the machines to ensure a smooth integration into the course. The largest such improvement was to replace all of the stock acrylic build plates with a custom designed aluminum and glass system manufactured in-house, as shown in Figure 3. The aluminum base is secured where the original build plate would sit as shown in Figure 4. A quarter inch thick sheet of glass is used as the build surface and rests inside the aluminum base on several pads that protect the glass from scratches and prevent it from moving while a print is in progress. This allows for easier build plate removal and replacement, and ensures that the build plate is completely flat, whereas some of the stock acrylic plates were found to be warped. In addition to upgrading the build plates, we removed the left and right cosmetic siding from the printers, which allows for easier cleaning and maintenance with increased access to the inside of the printer. Finally, we designed and 3D printed holders for all provided tools, and bolted them to the frame of the printers for convenient access.

Figure 3 - Redesigned Build Plate

Figure 4 - Build Plate Installed in Printer
Tools and accessories were selected for the printers in order to streamline the printing process. Glue sticks are provided at each printer, and a layer of this glue is applied to the glass before every print to help the part adhere to the build plate and prevent warping. Post-it notes are attached to the front of each printer. When a print is started, the student using the printer is required to write down relevant information so that the part can be returned to the correct team if the build finishes while that team is not present. Once the print is complete, the glass is removed from the aluminum base and is placed on a non-slip table surface to hold it securely while a slightly sharpened paint scraper is used to pry up the corners of a part. A painter’s palette knife is then used as a spatula. The thin metal tip can be inserted between the part and the build surface to completely separate the two. The glue is easily rinsed off with water, and then the build plate is dried with microfiber cloths, and returned to the printer. To store filament, and make changing colors and materials easier, the onboard filament system was replaced by racks of filament installed above the printers. When not in use, the ends of each spool of filament are held in a bracket installed on the wall behind the printer. This system allows each printer to have several easily interchangeable spools of rigid PLA plastic, as well as one roll of NinjaFlex, a flexible material. This equipment is all shown in Figure 5.

![Figure 5 - Tools and Equipment Provided at Each Print Station](image-url)
To simplify the system and to avoid confusion when referring to individual printers, the printers are currently connected to a central computer and named according to the NATO phonetic alphabet. Name tags were printed for each printer and they were named in the MakerBot Desktop software accordingly. This computer system allows multiple jobs to be initiated and run from a central computer and eliminates the need for SD cards in most cases. This computer network was not completely functional throughout the Fall 2014 semester, but was fully integrated prior to the start of the Spring 2015 semester.

Policy

During the Fall 2014 semester, the approach to the use of these printers was extremely hands-off and relatively unsupervised. Very few restrictions were placed on the printers and what could be built. All equipment was provided at the 3D print stations and the students were allowed to use the printers whenever the lab was open. During each section’s class time, each team had a dedicated printer that they could use for prototyping and builds under two hours in duration. If a longer print was required, a team could sign up for an overnight, extended duration print by signing up for a time slot through online scheduling software (SuperSaaS). The only restriction on extended duration prints was that a job might be canceled if the print ran into the 8 AM section the next morning. With this system that provided students with considerable autonomy when using the printers, it was possible to gauge which aspects of the system should be self-regulated and which needed more structure and supervision in the future.

After each print, students are required to fill out a 3D print form with details associated with the print. This inclusion provides a mechanism to collect data on how successful prints have been, how much material has been used, and if any printers require maintenance or servicing. This form requires contact information from the individual using the printer, as well as information regarding the part printed and the success of the print or perceived cause of failure. Upon the completion of this form, the student is sent an automated email response containing most of the information they entered, as well as the “cost” of their print. This cost is not actually imposed on the students (no currency exchanges hands), but the students are required to include this cost on their bill of materials for the project at the end of the semester. The cost for all printed parts must be included, regardless of whether or not the part is used on the final project. This policy is meant to emulate the real-world cost of this technology, where every prototype would have an associated cost that must be included when considering the budget for the project. The listed price for rigid PLA plastic in the Fall 2014 semester was five cents per gram of material used, and the price for the flexible material, NinjaFlex, was ten cents per gram. These prices are close to the actual price of the material, with little to no markup, to model a scenario where in-house additive manufacturing technology is used for prototyping. The 3D print log has also allowed the generation of usage and reliability data for each of the operational printers.
Patterns of failed prints are interpreted as a potential technical problem with one of the machines, and can be addressed immediately.

**Pedagogical Approach**

After creating a system for the printers to operate and be used by the students, it was necessary to instruct the students on how to use the technology properly and effectively. It was important to teach the students all of the steps and procedures necessary to operate the machines as well as use the software to create their physical parts. Because of the strong link between design software (CAD) and 3D printing, the two were incorporated into a single teaching module. The students learn how to create the parts in a CAD software package (Autodesk Inventor) and then go through the steps necessary to print the parts. The goal of the single module was to help strengthen the link between CAD software and design.

To address the need for a CAD/3D printing module, we developed the “3D printed car project.” Each student was required to print a few parts for a small electric car and at the end of the final assignment each team of eight students would have all of the parts needed to fully assemble their car as shown in figures 6 and 7. The car was designed by the teaching staff and works using almost entirely 3D printed parts. The car utilizes gears to produce enough torque for a single high RPM DC motor to propel the car at a moderate speed. Benefits of this car project include providing many different parts that illustrate the basic tools used in solid modeling packages and linking the CAD/3D printing to other aspects of the course (e.g., the gear drive train provides a working example of a transmission and is used to help students understand the transfer of mechanical power). Another benefit of the 3D printed car module was that the students could learn some of the logic behind additive manufacturing and understand how to modify their designs in order to create a part that can print accurately. For example, the wheels of the car help to demonstrate how to remove unnecessary material to reduce filament usage and print time, while also illustrating the correct use of thin walls at the right thickness to print without gaps on the Replicator 2 printers. There are also tolerances built into the model that allow the axles to fit securely into the wheels, and freely rotate in the chassis. The front axle was designed in two parts and assembled. This was done to avoid the use of support material that can be difficult to remove. The rear axle was printed with a thin sacrificial brim on the first layer, added in the CAD software, to give the part more surface area in contact with the build plate and prevent it from moving during the print. A section of the motor housing demonstrates bridging, a feature that allows the printer to connect two columns without support material. The small axles, cotter pins, tire treads, and battery pack are made of non-3D printed materials to illustrate that the printers are not the ideal solution for every application.
3D Printing Video Series

Before the students could begin the car assignment they first had to learn the general usage of the printers. A three part mandatory video series was created that walked the students through all required steps of creating their first 3D printed part. This video series was about fifteen minutes long and showed both the software and hardware steps required to print a part using the Replicator 2. After watching the videos each student should be able to take their CAD file and convert it into a stereolithographic format (.stl), a standard in the industry and the file type used in MakerBot Desktop that is compatible with the printers. Students then should be able to change all the required settings for the print and convert the part into a format that the printer itself uses, a type of g-code (.x3g). The videos then show how to use the printers from start to finish, detailing every step to emphasize correct operation. The videos were available to the students from the beginning of the semester so that they could watch them as many times as they felt necessary in order to feel confident in the process. When the students first used the printers they were required to execute all the necessary steps by themselves. If they had any questions they could always ask the teaching fellows or professors, but the goal of the video series was to help the students execute self-learning and rely almost entirely on the videos for the instruction.

CAD Video Series

After watching the video series on the correct operation of the printers, students are required to model the parts they are going to print in a CAD software package. In order to simplify instruction, only one CAD software package is used. Autodesk Inventor was chosen for this task primarily because it is a user-friendly solid-modeling software package that is seen as a good starting point for students who have never used CAD before. Each student has three ways
to access the software. They can use computers located in several labs around campus that carry
the program, they can use the Virtual Computer Lab which allows students to access the software
from their personal computer from anywhere with a University Login, or they can download the
free student package that Autodesk offers.

In order to avoid overwhelming students with CAD in a course that is focused on the
design of an autonomous vehicle, only five CAD assignments are required. These assignments
are a main component of homework that is assigned during the first half of the semester.
Students are only required to generate one part or assembly per assignment, with the exception of
the first assignment where two very simplistic models are assigned. The instructions for each
assignment are given in detailed videos that walk the students through every step required to
complete the assignment, from opening the program to creating an engineering drawing. For
each homework, every student is required to turn in an engineering drawing of the part they
create. As the course progresses the CAD assignments became more complex, and by the end of
the CAD module the students have been exposed to most of the basic functions and commands
within Autodesk Inventor. Not every part that is used for the car is covered in the CAD modules.
The .stl files for these parts are posted for the students to access when it is their turn to print. The
gears and motor housing parts were not covered in the videos due to the relative complexity of
these parts and lack of time within the instructional portion of the semester. However, students
use these parts when completing the culminating CAD assignment which is an Inventor
assembly of the 3D printed car.

By adding 3D printing to the CAD portion of the class it was hoped that students would
begin to appreciate CAD as more of a design tool than simply a tool to generate required images
for presentations. The 3D printed car module was meant to teach the students not only how to
use the printers and the CAD software, but also how to design a working assembly using additive
manufacturing practices. By requiring this assignment, students were able to experience multiple
steps in the design process from the design work in CAD software to the actual manufacturing
process of creating those parts. The hope was that this would allow students to then use CAD and
the printers to effectively design and prototype parts for their project in the second half of the
semester.

Supplementary 3D Printing Videos

While it was required for all students to gain some degree of experience using the
printers, resources were made available for those who were specifically interested in becoming
more proficient in the use of additive manufacturing equipment. Although this course is designed
to introduce students to a diverse set of engineering related topics, to explain every topic in depth
is impractical for the course structure. Therefore it is important to provide additional resources
for students to pursue the disciplines they wish to explore further. For the last week of the
instructional portion of the class, students decide on a specialty topic to study in more detail. For 3D printing instruction, advanced videos are provided to instruct the students on more in-depth techniques and complex design practices that allow them to become more efficient and knowledgeable about 3D printing. Certain design techniques that are specific to additive manufacturing, such as removing material to quicken print times or designing with tolerances, are discussed in depth. Students can then use these techniques for both their design project as well as future projects. Outside of the course, there are a number of resources available for the students to continue using additive manufacturing technology. Multiple labs on campus are open to engineering students and have varying types of machines for advanced manufacturing. The goal of these supplemental materials and resources is to allow students to take the knowledge learned in this course and have the skillset to apply it in the immediate future.

**Results and Response**

Near the end of the semester a survey was distributed to students currently taking the class as well as students from a past semester who did not have direct access to 3D printing technology. The survey was designed to indicate the subjective response from the students towards the 3D printing portion of the class as well as to note any changes between the behavior and attitudes as compared to students who took the course in a previous semester. The collected data was meant to gain insight into the effectiveness of the introduction of 3D printers and how to improve this portion of the class. The survey consisted of sixteen questions and took roughly ten minutes to complete. Approximately 630 students are enrolled in the class each Fall semester. Of those, 181 students from the 2014 semester responded, while 36 responded from the Fall 2013 semester. Due to the small sample size of the previous semester it is difficult to make any claims of statistical significance associated with student responses. However, though not significant, the results of the survey are promising.

**Printer Usage**

At the beginning of the implementation semester there were two main concerns with regard to the addition of 3D printers into the course. The first concern was whether the printers would be used by the students beyond the required printing assignments. The second concern was how reliably the printers would function if there was heavy usage. Due to the relative infancy of consumer grade 3D printing, machines can often behave unexpectedly and there was little known about how the printers would react to sustained heavy usage. At the end of the semester the concerns were found to be unwarranted.

The student response was overwhelming. During the heat of the semester the printers were running constantly and there was often a queue of several teams waiting to use each printer. Of those students who responded to the survey, 94.5% used 3D printed parts for their final
project, and of those students who were on teams that 3D printed parts, 61.3% personally printed some of these parts. This shows that the students wanted to use the printers. Many of these teams used the printers for several aspects of their projects. Figure 8 shows the number of times students used the printers beyond the required assignments. The results show that while some students did not personally use the printers, they were a minority. Of the students who responded, 73.5% used the printers after the required assignments and 36.5% of students were “heavy users,” using the printers five or more times.

![Figure 8 - Non-Mandatory Usage of 3D Printers](image)

Students were also able to create several unique and creative designs that would not have been possible using other manufacturing methods available. A representative example of this can be shown in a water testing apparatus that was designed and built by one of the student teams. This device incorporated a stepper motor, momentary push button sensor, thermistor, moisture sensor, and salinity sensor and was designed to allow the team to test the salinity, depth, and temperature of a pool of water. All other components of this unique device were created out of 3D printed parts. A CAD rendering of the system is shown below in Figure 9.
The printers were able to handle this enthusiastic usage effectively. The maintenance required to keep the printers running was manageable and could be completed by one or two trained technicians who spent about two to five hours each week maintaining or servicing the laboratory equipment. The most common problem is for the extruder to jam in some way, which could either be a blockage in the drive gear or a blockage in the nozzle. The first can usually be fixed quickly by disassembling the extruder, removing the blockage, and reassembling. In order to fix a nozzle jam, the nozzle has to be cleared out with a 0.4 millimeter drill bit, removed and cleaned with a propane torch, or replaced entirely. The next most common failure is that the filament cooling fan duct hits a part that has warped and breaks off. In this case, the duct can easily be replaced by one that is 3D printed. A few more serious, but less common problems have occurred, requiring the replacement of a part that cannot be made in-house. Twelve printers were purchased, ten for in-class usage and two were kept as spares in the event that a printer went offline. In this case, MakerBot has provided the required replacement parts, and the modular, open design of the Replicator 2 allows most replacements to be done in less than an hour. Whenever a printer was offline for an extended period of time, the two spare printers were substituted for the damaged one, and it was possible to keep five working printers in each lab for the duration of the semester.

**Part Success**

In addition to the student survey administered, a record of all print jobs and printer statistics was kept throughout the semester. Print jobs were logged through a Google Form that was intended to track every print that occurred in the labs. This print form required the students
to note the mass of all parts printed, the time used to print them, and whether or not the print succeeded. Total print hours were also compiled through tracking the stored lifetime print hours on each 3D printer to determine how consistently the form was completed by the students. There were no repercussions for failing to complete a print log, so students did not always log their jobs. Comparing the data showed that only about 50% of print hours were logged through the print log form. Total print material logged was 29.5 kg, which also accounts for about half of the 54 kg of material used during the semester. Of the jobs that were submitted, 88.6% were successful. It is possible that the number is skewed because there may be less motivation to log an unsuccessful print job. The failures that did occur were often due to poorly designed parts or failure to follow the proper print job procedure. Due to the freedom that the students were given with regard to the printers, they did not always adhere to good 3D printing practices. They would sometimes create large, unnecessary parts that took many hours to print, or forget important steps such as laying down adequate glue. These parts were prone to failure and since they usually occurred overnight there was no way to stop them when failure occurred. Another cause of problems was printers running out of filament. The printer often jams if it is still printing when there is no filament left. Due to the structure of overnight prints, it was often hard to tell if there was going to be enough filament to finish a job. Several policy changes have been instituted to help prevent problems such as these in future semesters.

**Student Reaction**

The responses to the survey regarding the integration of 3D printing were mostly favorable (Table 1). When asked, “Do you feel like you were adequately prepared to use the 3D printers for your project?” 91.2% of students in the Fall 2014 semester responded that they did feel adequately prepared. This demonstrates that the instructional method used in this class was effective at conveying the use of the technology. The question “Did you personally use CAD software to help design parts before making them?” showed that 56.4% of the students from the Fall 2014 semester did use CAD as a design tool, whereas only 36.1% of students from Fall 2013 had used it in that way. Similarly, when asked, “Please select ALL roles that you performed on your team,” 36.5% of students selected “CAD modeling specialist,” as opposed to 22.2% from Fall 2013. This is a notable jump, indicating that the addition of 3D printing as a course enhancement has likely increased the proportion of students who use CAD software extensively enough to list it as a specialty.
Table 1 - Summary of Survey Response Data

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>Fall 2013 Response (n = 36)</th>
<th>Fall 2014 Response (n = 181)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt adequately prepared to use 3D printers</td>
<td>N/A</td>
<td>91.2%</td>
</tr>
<tr>
<td>Personally used CAD software to design parts</td>
<td>36.1%</td>
<td>56.4%</td>
</tr>
<tr>
<td>Recognized themselves as CAD modeling specialists</td>
<td>22.2%</td>
<td>36.5%</td>
</tr>
</tbody>
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Furthermore, when asked, “What’s your current attitude towards 3D printing?” a conservative calculation showed that 87.3% of students who responded to this question had an undoubtedly positive opinion towards 3D printing technology, and the remainder had an opinion that was considered neutral or negative. Any responses that were ambiguous were deemed neutral or negative, even if they contained partially positive information. A typical positive response was, “3D printers are a technology that excites me and has huge potential. This was a valuable experience, and a fun one at that!” while a typical neutral response was “I enjoyed using them and may use them again. They were frustrating at times.” Some student concerns encountered in neutral or negative responses were found to be valid, and changes are being made to rectify these concerns and improve the efficacy of the system for future semesters. These concerns and changes are detailed in the next section.

Lessons Learned and Improvements

As with any newly instituted course component, much was learned from the first semester and there were many takeaways that we have already implemented into the second semester in order to make the process more effective and beneficial as a whole. After reading responses to the survey and discussing individual experiences with the teaching staff, changes to policy, CAD video instruction, 3D printing video instruction, and CAD assignments have been implemented. These changes are evaluated throughout the semester to continually improve the course. Any improvements that can be made are typically implemented quickly across all sections of the course to ensure the best possible experience for students and faculty. The effectiveness of the system is given priority over the collection of rigorous statistical data, and for this reason, there was no experimental “control group” of students who were denied access to the new technology or what was deemed superior instructional materials. This approach is consistent with the design-based implementation research methodology that Penuel et al. propose\textsuperscript{22}.

Policy changes have been implemented to reduce the number of failed prints and malfunctions, and increase the regularity of the feedback received through the print logging system by holding students more accountable for their 3D printer use. Each team is given a 3D
print card once they watch all required 3D printing tutorial videos and receive a passing grade on an electronically administered 3D printing quiz. This card may be used to rent one 3D printer, and the card is not returned until the print station is clean, the tools are in the correct holders, and the build plate is cleaned and returned. In addition to this, while teams still have exclusive access to a dedicated printer during their class period, there are more restrictions and supervision for overnight prints. A time limit is imposed on all prints, and special authorization must be given for prints longer than four hours. Prints longer than eight hours require a design consultation to discuss the part. If the part is not well designed for 3D printing or can be made more efficiently with a different manufacturing method, it will not be approved. If the part is well suited for 3D printing, methods to remove material or improve the performance of the part are discussed. These policy changes are expected to reduce part failure rates and wasted time and material, while enforcing better time management by requiring the students to be prepared early. Material costs have also been increased from five to ten cents per gram for PLA parts and from ten to 15 cents per gram for Ninjaflex parts to discourage frivolous use of the printers. As before, this cost must be included on the team's bill of materials even though no payment for the printed parts is required. In addition to required design consultations for long prints, all students now have the opportunity to request a consultation to receive directed instruction and feedback related to designing parts in CAD specifically for 3D printing.

The CAD instructional videos have been modified to better incorporate the link between CAD and 3D printing. For the first semester, the main goal of the videos was to just show all of the steps necessary to make the parts. While the videos were effective in teaching the students how to create the parts, the connection between CAD and manufacturing was not emphasized. An additional goal of the videos for the second semester is to show the link between 3D printing and the CAD models that are being created. Instead of just showing the steps necessary to make the part, the videos now emphasize the design considerations that are present in each part. For example, the rear axle video discussed how to create a chamfer on an overhang to avoid the use of support material. By adding explanations such as these to the videos the students should be able to see how some design challenges were met, and understand how to make similar decisions when they encounter problems in their designs.

Based on the survey responses, some students felt that although they understood how the printers functioned and were able to replicate parts for the car assignment, they were unable to create original designs in accordance with good 3D printing practices. The students did not get to practice creating novel designs for 3D printing until the final design project. This lack of practice caused some teams to make poor decisions for their project. In order to supplement their knowledge about CAD and 3D printing a new assignment is being created that requires each student to individually design a part within a set of constraints (e.g., cost and print duration, tolerance of fit, performance criteria). For the assignment each student will be given an
engineering drawing of an Arduino Uno microcontroller and asked to design a retention mechanism that could be used to mount the device to the chassis of their vehicle. In order to complete the assignment students will have to understand important techniques in 3D printing such as how to design with tolerances and avoid extreme overhangs. There will be no video detailing exactly how to generate the part so the students will have to draw on lessons from previous videos as well as supplementary videos on designing for 3D printing in order to create their own design. Each team will then pick the best design from the group and print this design. This assignment will be implemented in the Fall 2015 semester.

Excluding the new CAD assignment just described that will be implemented next academic year, all of the improvements described have been put into effect for the current semester and are under evaluation. Some changes appear to have already had a clear impact on the effectiveness and efficiency of the system. The addition and enforcement of the 3D print card system has dramatically improved the cleanliness of the print stations. All build plates are washed after each use, tools are stored properly, and according to preliminary data, a much higher percentage of print jobs have been logged this semester. Additionally, less printer maintenance has been required. The formalized and unfamiliar structure of the 3D print cards proved to be difficult to implement initially; students were able to use their student ID cards to reserve the printers during this period. While some of the improvements observed so far may be attributed to improved instructional materials and policies, it's likely that faculty and teaching assistant familiarity with the hardware and its capabilities/limitations following the Fall 2014 semester is contributing to a more seamless experience in the current semester. Thus far, there have only been a few design consultations, because the design phase of the project has only just begun. In all of these consultations, it has been possible to help the students refine their design to reduce the material use and print time. The addition of these policies, the improved and interlinked instructional material, and the new channels and opportunities to receive feedback and support have allowed for a reduction in filament used and an improved experience for the students.

Scalability

Implementation of 3D printers in a first-year engineering design course and the instructional method described may be scalable for use at other institutions. Given the number of students and team based structure of the class at the authors’ institution, it was decided that ten printers were sufficient for the needs of this class. Each section of the course had five teams, so each team had access to a dedicated printer during their section’s class hours (four hours per week). To maintain ten operational printers at all times, it was decided to purchase two additional machines as spares. This was adequate for most of the semester, but there was a period of several weeks where every printer (including the two spare printers that were put into service) consistently had a long queue of teams waiting to print their parts. Some of the new restrictions
and policies should serve to reduce this demand on the printers, and compel students to consider other production methods more seriously before turning immediately to the printers.

The incorporation of CAD and 3D printing instructional videos has reduced the amount of in-class time required to address these topics and the proficiency that each section instructor requires in the use of this technology. In this manner, this pedagogical approach for a large, multi-section course appears scalable to any number of sections provided the number of 3D printers available are sufficient to meet the needs of students and some members of the instructional team have expertise in the use of the equipment.

The authors estimate the cost of each printer with the modifications described to be about $2300. During the Fall 2014 semester, the student to printer ratio was 64:1. This ratio was reasonable to meet the needs of the course, though during the times in the project when demand was highest the availability of additional printers would have been welcomed. The procurement of two spare printers (20% of the number made available to students) also appeared appropriate to ensure that there were 10 operational printers throughout the semester. During the Fall 2014 semester, approximately 54 kilograms of PLA filament were used by students. The average cost of PLA filament purchased was about $26 per kilogram. With 640 students enrolled in the course working in teams of eight, two separate metrics for the amount of filament required can be computed. On a per-student basis, 84 grams of filament is required at an average cost per student of $2.20. On a per team basis, 0.675 kg of filament is required at an average cost of $17.55. The filament costs should reduce as the policy revisions described requiring special permissions and design consultations for long duration prints are implemented. The ongoing material costs associated with this technology appear very reasonable when weighed against the opportunities for learning made available through the introduction of 3D printers into a first-year engineering design course.

Conclusion

Overall, the implementation of 3D printing technology into the curriculum had a positive effect on the course. It was met with interest and enthusiasm by both the faculty and the students. This paper has described the process by which this new technology was incorporated into the course and the lessons learned to improve the use of 3D printing within a first-year engineering design course that requires the construction of a prototype. While some aspects of the methods used in the first semester required immediate revision, the introduction of 3D printing is seen as a course enhancement that should be refined, improved, and continued in future semesters. Additionally, the blended learning instructional method described allows for the inclusion of 3D printing technology in first-year design courses to be easily scaled to accommodate the size and needs of other similar courses without requiring excessive faculty training in the use of 3D printers or the dedication of significant classroom time. Linking CAD instruction with 3D
printing assignments allowed every student to gain first-hand exposure to 3D printing technologies and to directly see the powerful connection between CAD modeling and manufacturing. Consumer-grade 3D printing technology allows the relatively low-cost addition of manufacturing equipment into the undergraduate curriculum. This addition should help to bridge the knowledge gap between CAD modeling and production. The initial data shared indicates that the introduction of additive manufacturing as a course enhancement has increased the number of students who choose to gain substantial experience with CAD software. Future work should examine changes in student motivation to learn CAD as a result of having required 3D printing instructional activities, and how an early exposure to the direct link between CAD and manufacturing gets utilized by engineering students throughout their undergraduate studies.

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References


