New Inexpensive 3D Printers Open Doors to Novel Experiential Learning Practices in Engineering Education

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Abstract

This work describes a set of new inexpensive 3D printers and their applications in experiential learning as part of engineering education encompassing two multidisciplinary undergraduate engineering programs, Mechatronics and Industrial Engineering. The work addresses applications of inexpensive 3D printers in support of many engineering and non-engineering courses and activities at our university. Challenges of running a successful 3D-printer lab are addressed. A number of student projects are described. Based on the shear amount of 3D prints and their quality it can be concluded that the acceptance of this technology is high within the undergraduate engineering student population.

Introduction

Early laboratory demonstrations of additive rapid prototyping systems were conducted thirty years ago (1984). However, the acceptance of these systems in undergraduate engineering curricula was relatively slow due to the high cost of the equipment, the high cost of the materials used, and the high maintenance costs. Only a few engineering departments could afford such machines. Even then, 3D printers were mostly used for demonstrations or a limited number of student projects. However, recently this changed. Namely, a new breed of rapid prototyping machines, the inexpensive 3D printers, based on the fused deposition modeling (FDM) process emerged. Such 3D printers "build" three-dimensional objects by depositing multiple layers of molten plastic, one on top of the other. Instead of paying $100,000 for a single rapid prototyping machine as of a couple of years ago, an engineering department can now equip a whole rapid prototyping laboratory with ten 3D printers for under $20,000. For example, Afinia H-Series and UP Plus 3D Printers cost $1,599, MakerBot Replicator 2's cost $2,199 while Replicator 2X's cost $2,799. Also, the plastic filament, acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), costs between $23/kg and $48/kg, dissolvable filament costs $65/kg, while translucent plastic and flexible filament cost $130/kg. This affordability creates a number of new possibilities for 3D printers' use in engineering education.

Benefits of using 3D Printers in Engineering Education

The benefits of using 3D printers in engineering education are many. Now, students can create inexpensive functional plastic parts early in their studies. Even before learning how to create 3D solid models in any of the computer-aided design (CAD) programs (usually taught in the freshmen year) students can download object files from the Web and create 3D objects from them. At the beginning stages of students' development of 3D visualization skills through CAD programming, an instructor can 3D print some of the parts that are hard to visualize. Then, as soon as the students become proficient with CAD programming they can verify their designs by creating 3D printed parts without having to machine them.

Machining skills are usually not emphasized in many engineering curricula. Students are exposed to machining processes such as turning, drilling, milling, grinding, welding, casting, molding, etc. in their second or third year of study in mechanical, industrial, or mechatronics engineering curricula. In other engineering disciplines students may only receive a rudimentary

exposure to manufacturing methods. Now, by using 3D printers, students don't have to wait to their junior year to create something. They don't have to be proficient as machinists whether using manual or CNC machines. Even when students are capable machinists, the availability of lathes, milling machines, welding stations, CNC machining stations, or other manufacturing equipment is often limited. Machining of many complicated parts requires a number of steps (setups, jigs, fixtures, etc.) that are rather time consuming. Unless a part must be made of metal and requires high precision, it is much faster to design and 3D print such part in plastic – at least at the initial design stages.

Supervision and safety of students in a machine shop are always high priority for machine shop coordinators. At most institutions, students are not allowed to work alone in machine shops due to safety concerns. In 3D printing, except for the high temperatures of the extruder assembly and the build platform (for ABS plastic only), there are very few safety concerns. The 3D printing process is mostly a hands-off process. During printing, there are no forces that can propel plastic parts and cause injuries. During the 3D printing process, except for the recommendation to 3D print in a well-ventilated area when printing with ABS plastic due to unpleasant fumes, and not to touch the hot nozzle, there are no other safety concerns. When removing parts from the printer, there are no sharp metal chips or metal edges that can cause serious injuries to students. However, one must be careful when releasing a part (mostly PLA) from the build plate since PLA adheres well to the platform and often a sharp object is used to remove the part.

Students' success in undergraduate engineering programs is attributed to three students' characteristics: intelligence, intellectual curiosity, and grit. It can be argued that 3D printing increases students' intellectual curiosity since it provides fewer steps from "imagination to realization." Also, since students can create real objects in many design phases, they can stay on task longer then before, thus increasing grit.

Previous Work

The value of experiments, laboratory exercises, and other hands-on experiences in undergraduate engineering education is well established through Kolb's Experiential Learning Cycle theory. The use of rapid prototyping machines and more expensive 3D printers aiding visualization in engineering graphics courses, teaching additive manufacturing methods in manufacturing courses, and building of prototypes in engineering design courses are well documented in the literature.

Kolb's Experiential Learning Cycle theory[1] claims that regardless of the learning style, a student learns most efficiently if he/she follows a cycle consisting of four steps (axes): experiencing (concrete experience), watching (reflective observation), thinking/modeling (abstract conceptualization), and applying/doing (active experimentation). Kolb's learning cycle has been used in various engineering education programs such as civil[2-4], mechanical[4], chemical[2, 3, 5], industrial[6], aeronautical[4], and manufacturing[2, 3, 7] engineering. Thus, active experimentation like building mechanical objects as visualization aids, building mechanical parts as a new manufacturing process, and building prototypes as steps in the design process or research, is an essential part of the learning process.

The success of rapid prototyping projects in engineering education, albeit using expensive 3D printers, has been well reported in the literature. Walsh, Griffin and Crockett[8] use a Z-Corporation 3D Printer in biomedical engineering courses. Lai-Yuen and Herrera[9] design a

medical device for a surgeon in their manufacturing processes course using an FDM Dimension and a ZCorp 3D printing machine. Leake[10] uses Genisys XS and a Dimensions 3D printer, both from Stratasys, to develop and deliver a new course on Computer-Aided Design, Manufacturing and Engineering (CAD/CAM/CAE). In architecture, Guidera[11] uses a Stratasys 758 BST 3D printer to fabricate a model of an office tower. In his junior-level mechatronics course in a mechanical engineering program Garner[12] prints plastic parts for a printer using a Dimension uPrint FDM 3D printer. Chiou[13] et al. also use a Dimension uPrint 3D printer to fabricate plastic parts for a walking robot in their robotics and mechatronics course. However, the prices of the 3D printers used in the above research as well as the maintenance and material costs are high precluding such 3D printers to be fully integrated into undergraduate engineering education. For example, uPrint 3D printers start at $14,900 which is about an order of magnitude higher than UP Plus 3D printers.

While inexpensive, the 3D printers used in our 3D-printing lab are still based on the newest hardware and software developments. MakerBot's Replicator 2 was introduced in September 2012, while Replicator 2X started shipping in limited quantities on February 25, 2013[14]. The purchase order for our institution was delayed from January to July of 2013 due to manufacturing problems. The Makerware 3D-printing software was upgraded in September of 2013[15] to include dissolving and flexible materials.

Engineering students should become familiar with 3D printing technologies because the 3D printing revolution (for product design and manufacture) is in its full swing. Attesting to this is a 3D printing pen 3Doodler, a successful Kickstart project to be released to the public in March of 2014; however, a Chinese company is already selling its clone version. Being proficient with 3D-printers is in line with ABET General Criterion 3, Student Outcomes[16] (c) "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" and (k) "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."

The Technology: Inexpensive 3D Printers using Fused Deposition Modeling

The 3D-printing lab consists of two UP Plus 3D printers, two Replicator 2 printers, three Replicator 2X 3D printers, and one Thing-O-Matic 3D printing kit (not used). The inexpensive 3D printers use FDM rapid prototyping process where a small diameter nozzle deposits heated plastic filament first onto the build surface and then in subsequent passes onto the previous layers thus fusing the layers and creating plastic objects. Even though the 3D printers in the 3D-printing lab are using the same FDM technology the printers' characteristics are notably different.

All 3D printers in the lab use the same 1.75mm diameter filaments size and have the same nozzle diameter of 0.4 mm. A comparison of printer characteristics is tabulated in Table 1.

Table 1. 3D Printer Comparison

3D Printer / Characteristic	UP Plus	Replicator 2	Replicator 2X
Material	ABS, PLA	PLA, Flexible	ABS, PLA, Dissolvable
Heated Platform	Yes	No	Yes
Platform Material	Aluminum	Acrylic	Aluminum
Platform Removal	Hard	Easy	Hard
Dual Extrusion	No	No	Yes
Print Volume LxWxH	5.5x5.5x5.3 in 14x14x13.5 cm	11.2x6x6 in 28.5x15.3x15.5 cm	9.8x6.3x5.9 in 25x15x15 cm
Enclosed Print Volume	No	No	Yes
Software	UpWare	Makerware	Makerware
Connectivity	USB	USB, SD Card	USB, SD Card
File Types	STL	STL, OBJ, Thing	STL, OBJ, Thing
Layer Resolution	0.15mm	0.1mm	0.1mm
Price ($)	1,599	2,199	2,799

While our 3D printers can only print in ABS, PLA, dissolvable plastic, glow-in-the-dark plastic and flexible plastic, other more-expensive 3D printers (some of them not yet commercially available) are capable of printing objects in Aluminum, Titanium, sugar, glass, and chocolate.

ABS and PLA are popular thermoplastic printing materials. ABS glass temperature is 105°C while PLA glass temperature is 60-65°C. Both materials extrude well at nozzle temperatures around 230°C. ABS is soluble in Acetone thus allowing rework and "welding" of parts after printing. However, ABS requires a heated printing platform (about 110°C) covered in Kapton tape since ABS does have a large temperature-shrinkage coefficient and it does not bond well with many materials. ABS has a tendency to "curl up" away from the printing platform resulting in failed builds. Also, the fumes during printing may be toxic so good ventilation is required. In contrast, PLA printing does not produce unpleasant fumes; PLA bonds better, and it has lower temperature-shrinkage coefficient thus it does not require a heated printing platform. However, there are only few types of glue that work with PLA. Neither material is easy to recycle even though PLA is considered more "earth-friendly" because it is biodegradable, compostable (in commercial composts only), and made from corn, potato, sugar-beet, or sugar-cane starch.

ABS parts can withstand higher temperatures, are more flexible, and do not degrade as quickly in the outside environment. PLA parts are more rigid, glossy, and show greater detail.

The differences in printing software are also notable. The Makerware printing software includes options for all of MakerBot printers and their new 3D scanner. Makerware is an upgrade to the company's ReplicatorG software. The program allows the user to choose one of the two nozzles or two-filament printing for Replicator 2X and the type of plastic. The program accepts STL or THING file formats and creates X3G slice files that can be stored on SD cards (2GB or less) for printing. Figure 1 shows a screenshot of Makerware printer software with "peaks" MATLAB function.

Figure 2 shows a screenshot of UpWare printing software for Up Plus 3D printers. The software requires a USB connection between the 3D printer and the computer to transfer the slice program to the 3D printer directly when the user clicks the Print menu button. Once the program is transferred, the computer can be disconnected from the printer. One helpful feature of UpWare is that the program calculates and displays estimated object completion time.
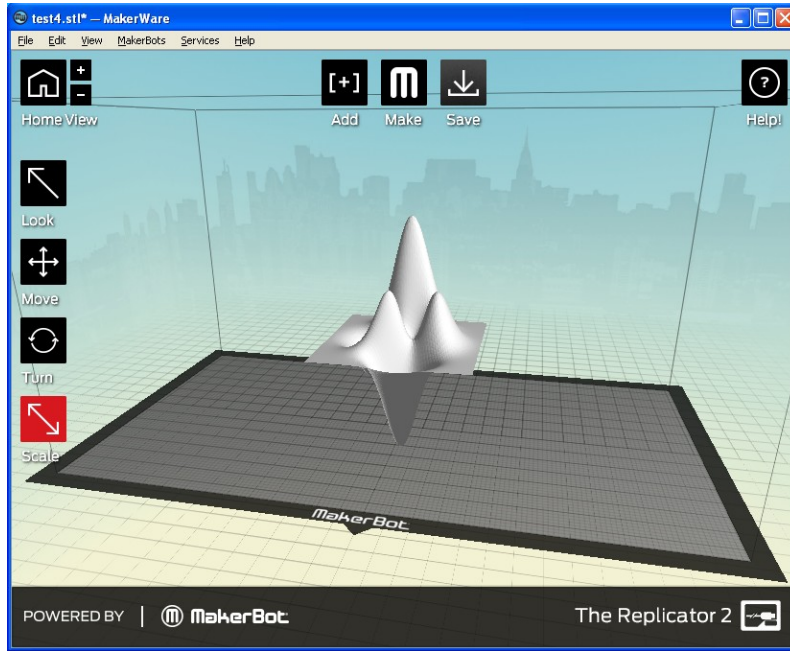

Figure 1. Screenshot of Makerware Printer Software with "peaks" MATLAB Function
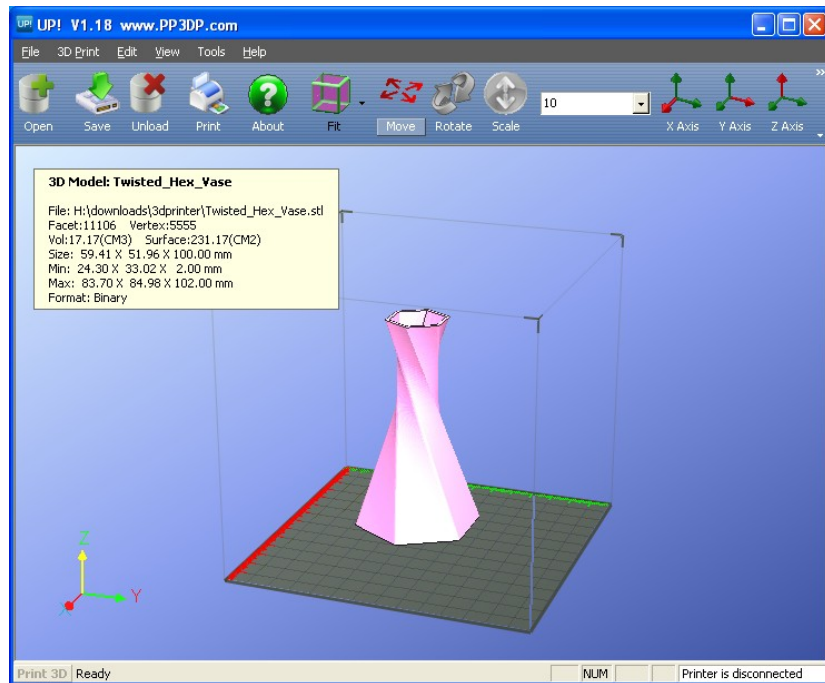
Figure 2. Screenshot of UpWare Printer Software with a Vase

Apart from the low cost of the new 3D printers themselves, another major advantage of this technology is the low cost of the materials used. Table 2 shows a partial list of objects built in the 3D-printing lab with associated material costs.

Table 2. A Partial List of Objects, Weights and Material Costs

Part	Material	Weight (g)	Cost ($)
"Peaks" function MATLAB	ABS	17	0.82
3D Mobius Curve	PLA	25.31	1.22
Thunderwolf (1/2)	ABS	19.91	0.96
Gear Cube with Stand	PLA	77.12	3.7
20 mm Cube	PLA	3.12	0.15
20 mm Cube on UP!3D	ABS	5.03	0.24
Pumpkin	ABS	29.13	1.40
Tension Test Specimen	ABS	7.23	0.35
Tension Test Specimen	PLA	9.25	0.44
Saturn Rocket	ABS	60.26	2.89
Snowman	ABS	27.87	1.34
Yoda	ABS	37.78	1.81
Lamp	ABS	74.33	3.57
Ghost (big)	Glow-in-the-Dark	42.81	5.57
Rings (5)	Flexible	0.75	0.1
Ball Bearing	PLA	20.73	1.00
Comb	PLA	6.28	0.30
Frog	PLA	3.11	0.15
Bracelet	PLA	4.60	0.22
Quadcopter (1 leg)	ABS	49.78	2.39
House	ABS	104.07	5.00
Centrifuge for Dremel	ABS	13.30	0.64
Cube for education (1/6)	ABS	19.95	0.96
Chocolate Bunny Mold (1/2)	ABS	21.81	1.05

3D-Printing Lab Policies and Procedures

Figure 3 is a photograph of our 3D-printing lab consisting of seven inexpensive 3D printers. The two 3D printers in the foreground are Replicator 2's. The 3D printers are simple to operate and require little maintenance. There is one student lab assistant that works eight hours a week on helping students run their designs, performing printer maintenance and repairing printers when needed. The assistant installs filament as needed or when requested by students. Every week the lab assistant makes sure that all platforms are leveled as per set-up printer programs.
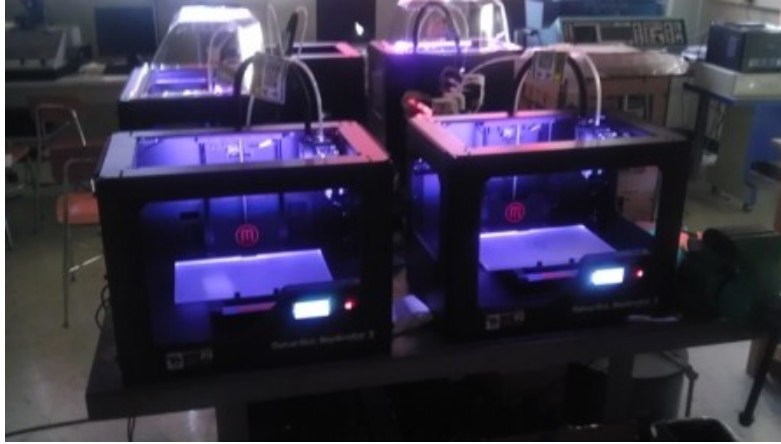
Figure 3. The 3D-printing Lab

There are two types of labs instituted: the instructor-run labs which are the labs specified in the syllabi of the engineering courses and the open labs (eight hours a week supervised by the student lab assistant). During open labs any individual (not necessarily a student) may print any object as long as such object is approved by the professor in charge of the 3D-printing lab. However, the priority is given to students doing course-related lab work. Excessive use of the lab for printing multiple objects not related to a student's course of study or for printing inappropriate objects is subject to disapproval by the professor in charge. Inappropriate objects are objects that may be construed as offensive or illegal.

Since the establishment of the 3D-printing lab last summer, hundreds of objects were created. A number of stretchable bracelets and small frogs were built for outreach activities. In manufacturing courses like Engineering of Manufacturing Processes and Computer-Integrated Manufacturing each student is required to print at least one object. Since Replicator 2 and 2X printers keep track of their hours of usage this information shows the extent of use. Just during the last semester the total 3D printers' usage for two Replicator 2, three Replicator 2X, and 2 UP Plus 3D printers (estimated) was over 700 hours. Since the working printers are rarely left unsupervised the student's usage limit was not due to the parts and their size/density but was due to the print time required.

Engineering faculty are trying to engage students to use novel technologies, thus the students do not pay a fee when they want to print something that's not related to their courses. The rationale is simple. If a student is designing an object like a doorknob, he/she still has to use SolidWorks for this design, choose the material, and print the object. Even creating a print file used by the printer is a useful engineering skill since not every object yields to an easy build. In addition, the fee-based lab would be hard to manage without any real monetary gain since the material is about $23/kg and most parts are in the order of a few grams.

3D Printing Lab Experiences
There are many software choices when designing objects for 3D printing. All major CAD software packages support creation of STL files. While an average 3D printer user outside the engineering education system may use free software packages like Google SketchUp or Blender, most of the students at our institution designed their creations in SolidWorks. One student used

SolidEdge while two others used SketchUp when working at home. Sometimes, it is necessary to take a 2D drawing and turn it into a 3D printable object. Inkscape is a vector graphics editor that can manipulate Scalable Vector Graphics (SVG) files to create 3D objects and it can save such objects in a variety of file formats including the Drawing Exchange Format (DXF) which is used by many CAD programs.

In the 3D lab, there are three types of printers that mostly use two types of plastic filaments. Since the Makerware X3G object files that control the printers include the printer and the material information there was a need to establish a file-naming convention for these files. The files for Replicators are named using the following format Description(Initials)-ExtruderMaterial.x3g. Description is one word or a short phrase; Initials are the author's two or three letter initials; Extruder is either right (R), left (L), or omitted, and Material is either PLA (P) or ABS (A). For example, *Gripper(NJ)RA.x3g* denotes that a gripper will be printed using the right nozzle of a Replicator 2X 3D printer with ABS material. This also means that for a successful print the printing surface needs to be prepared to fit the material. UP! printing program sends files in real time to the UP Plus printer, thus it does not require a file-naming convention.

In general, PLA prints are performed on a glass or a plastic platform that is not heated. However, since ABS contracts much during cooling and it does not adhere to the surface of the platform well, the platform is heated and it is covered with Kaptone tape. Kaptone tape is made of a polyamide film with silicone adhesive. Kapton adheres well to ABS plastic and works well within a large temperature range (-269°C to 260°C).

Usually, parts made of ABS plastic easily separate from the platform. However, PLA parts stick well to the platform and their removal is a bit more challenging. Most of the time, the PLA platform of the Replicator 2 printers needs to be removed before the object is separated from it. The platform removal and mounting are fairly easy and straightforward. Small steel spatulas from Cricut, chisels, pliers, cutters, Dremel tools with appropriate bits, etc. are used to separate objects from the platform and from the supporting material.

For after-printing touch-ups and rework three techniques are implemented. A new device, a 3D printing pen 3Doodle (shown in Figure 4) complements a regular 3D printer by fixing print flaws, or adding hand-drawn 3D features in plastic. The first 3D object created in the 3D printing lab by using a 3D pen is shown in Figure 5. A soldering iron is used for "welding" parts together or for repairing some minor flaws without adding material. Sometimes, acetone is used for gluing ABS parts together. In addition, a glossy surface in ABS may be obtained by depositing a small amount of acetone using a brush. The surface color can be changed by brushing on a thin layer of ABS plastic/acetone mixture.

Large, high-density parts may take considerable time to print. Even the printing time for some medium-size parts can take hours. We found that when printing medium-to-large parts it is useful to set up an on-line monitoring system. In the past, a laptop with a camera pointed towards the 3D printer and connected to the Web was used to monitor the process. Students, lab assistants, and professors monitored their builds.

Within the last year, there were two malfunctions of 3D printers. One UP Plus 3D printer stopped heating the base plate. The professor in charge of the lab ordered the required heater and

replaced it. Also, one of the Replicator 2X 3D printers stopped moving in the Z-axis. The student lab assistant troubleshot the system and found that one of the wires was cut by the repetitive motion of the 3D printer. He then ordered and replaced the wiring harness that had the broken wire. After searching the Web he found a workaround for the problem which resulted in a small hardware change. Now the wires in our Replicator 2X 3D printers don't bend as sharply as they did before so the repetitive motion of the printer will most likely not break that wire.
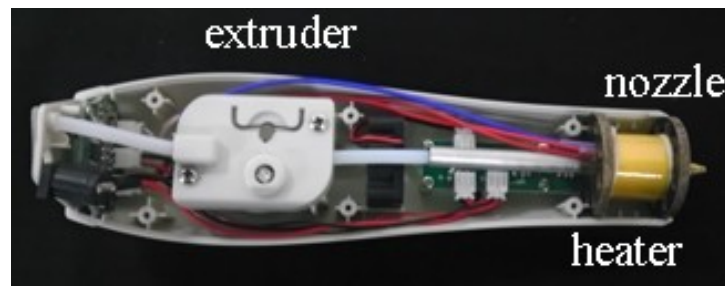
Figure 4. 3D Pen Showing Major Parts
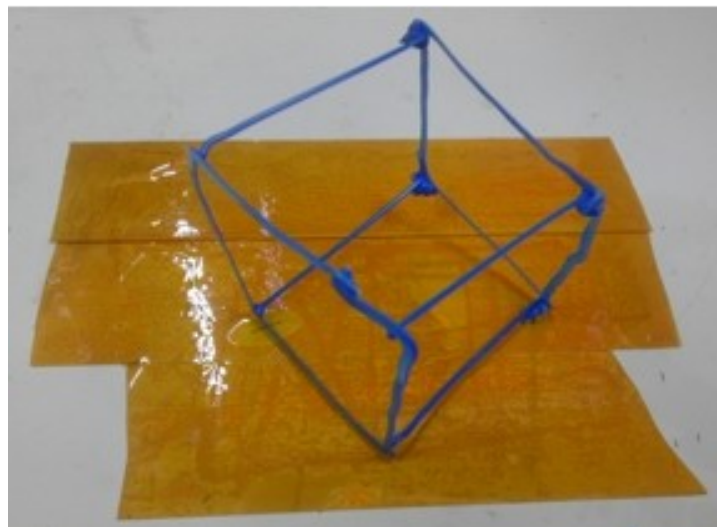
Figure 5. 3D Object Created using 3D Pen Extruding ABS Plastic on Kaptone Tape

3D Printing Applications in Engineering Curricula

The 3D printers described in this work are used in a number of required courses at our university in two undergraduate engineering ABET accredited programs: Bachelor of Science in Engineering with Specialization in Mechatronics (Mechatronics) and Bachelor of Science in Industrial Engineering. Table 3 lists the engineering courses that use 3D printers. A short description of 3D printer application(s) in each of these courses is given next.

Table 3. Undergraduate Engineering Courses with 3D Printer Applications

Course	Objective	Object	Cost ($)
Introduction to Engineering	Demonstration	Bracelet	0.22
Engineering Graphics	Visualization	Ball Bearing	1.00
	Visualizations	Lamp	3.57
Calculus and Analytic Geo.	Visualization	3D Mobius	1.22
Problem Solving for Engineers	Visualization	"Peaks"	0.82
Materials Science and Eng.	Tensile Strength Test	Specimen ABS	0.35
	Tensile Strength Test	Specimen PLA	0.44
Thermodynamics	Example	Engine	1.50
Quality Control and Reliability	Example	20 mm Cubes	0.24
Eng. of Mfg. Processes	Comparison with CNC	20 mm Cubes	0.15
		20 mm Cubes	0.24
	Pattern creation	Thunderwolf	1.92
Computer-Integrated Mfg.	Applications	Various Designs	<5.0
Controls I and II	Applications	Various Designs	<5.00
Projects	Applications	Various Designs	Varies
Physics (in progress)	Visualization	Wave Equation	<3.00

Introduction to Engineering

In this course, class time is set aside so that each engineering faculty member can introduce the first-year students to his/her engineering emphasis. So, for one class hour students come to the 3D-printing lab, start printing a bracelet, listen to a short lecture on rapid prototyping, and then remove their parts from the printers. With about 20 to 25 students per class and seven printers all students are able to take part in printing bracelets. However, since the last batch of students don't get to release their parts, since their parts are still printing by the end of the class period, they can take home some already made bracelets. Figure 6 shows some of the printed bracelets. In addition, students have an opportunity to see the rest of our 3D-printed gallery. They particularly like "Yoda" depicted in Figure 7.

Figure 6. 3D-printed Bracelets

Figure 7. Yoda

Engineering Graphics

This course deals with mechanical designs and drawings. Tree-dimensional visualization skills are developed in this course. However, for some students this is hard. Sometimes, holding a part in their hands helps. Also, a real part shows students that their Computer-Aided Design skills with SolidWorks may produce 3D objects. Here, only a couple of objects are printed using a 3D printer. They are used as examples. In the future, best student designs will be 3D-printed. Examples like a sphere, a turbine, or ball bearings (the whole assembly is printed together) are shown in Figure 8.

| Sphere with a Screw | Turbine | Ball Bearings |
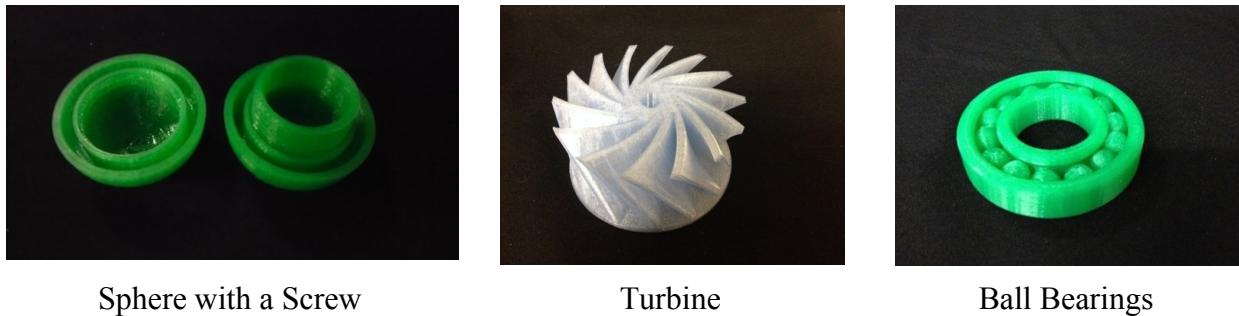
Figure 8. Example Parts for Engineering Graphics Course

Calculus and Analytic Geometry

3D-printed models of various functions are used for visualization. A toroid, a 3D Mobius curve, or a "peaks" 3D curve can be created in MATLAB or Mathematica, saved as an STL file and then sliced by the 3D printer software before printing. For example, 3D-printing of "peaks" function can be accomplished by using MATLAB to create an STL file as follows:

>> z=peaks(25);
>> mesh(z);
>> surf2stl('test.stl',1,1,z);

where *surf2stl* is a function downloaded from the Mathworks website[17] residing somewhere in the MATLAB PATH, while *test.stl* is the created file. Figure 9 shows a toroid, a 3D Mobius structure, and an another 3D function. Figure 11 shows a 3D build of "peaks" surface usually seen in MATLAB literature. In this case, the support material is left with the object since the MATLAB had problems creating a solid 3D object. Also, the original solid model was scaled 5:1 in Z direction to closely resemble the scaled 3D drawing as shown on the computer screen (Figure 10).

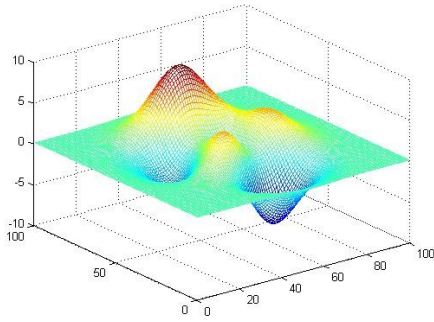Figure 9. Example 3D objects for Calculus I Class

Figure 10. "Peaks" 3D Surface in MATLAB   Figure 11. 3D printed "Peaks" 3D Surface

Problem Solving for Engineers

This is the first course in programming for freshmen. The course uses MATLAB as a programming environment. Figure 12 depicts a 3D surface generated in MATLAB. This surface was transformed into a solid model (in MATLAB) and then built using a Replicator 2X in ABS plastic (Figure 13).
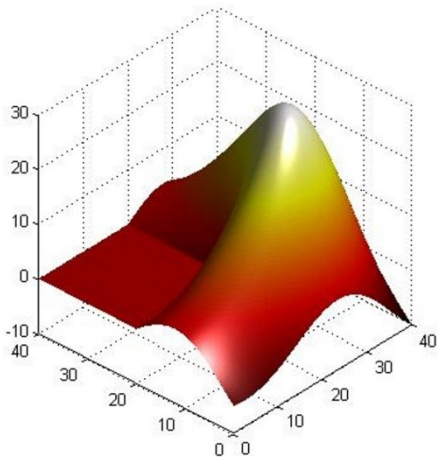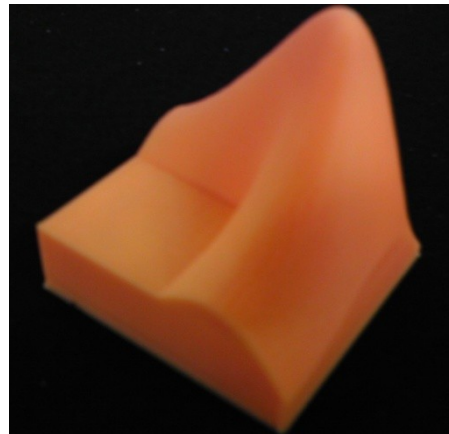

Figure 12. 3D Surface created in MATLAB   Figure 13. 3D printed Solid Model Originally Created in MATLAB

In this case, the following MATLAB code was used to create the plot of Figure 12 and to create a solid model from the surface in STL format suitable for 3D printing. Two MATLAB functions *surf2solid*[18] and *stlwrite*[19] were downloaded from the MATLAB Central website. It is assumed that these files are in the MATLAB PATH, otherwise, the user needs to change to that directory before running the program. The program below creates a *surf2solid_block.stl* file which serves as an input file to the 3D printer program.

```
>> n=200;
>> [X,Y] = meshgrid(linspace(0,40,2*n+1));
>> L = membrane(1,n)*30;
>> surf(X,Y,L,'EdgeColor','none'); colormap hot; axis image; camlight;
>> horizonLevel = -12;
>> FV_block = surf2solid(X,Y,L,'elevation',horizonLevel);
>> stlwrite('surf2solid_block.stl', FV_block)
```

Materials Science and Engineering

This course has an associated lab where students perform tensile strength tests. In one of the lab session, students create composites and tensile test specimens. Using ABS and PLA test specimens students measure tensile strength of these materials. Figure 14 shows three tensile test specimens, two PLA and one ABS before the test.

Figure 14. Tensile Test Specimens

Thermodynamics

For purposes of this course (there is no lab associated with the lectures) one of the students from a local community college created a plastic model of a single-cylinder engine. Figure 15 shows elements of the engine.
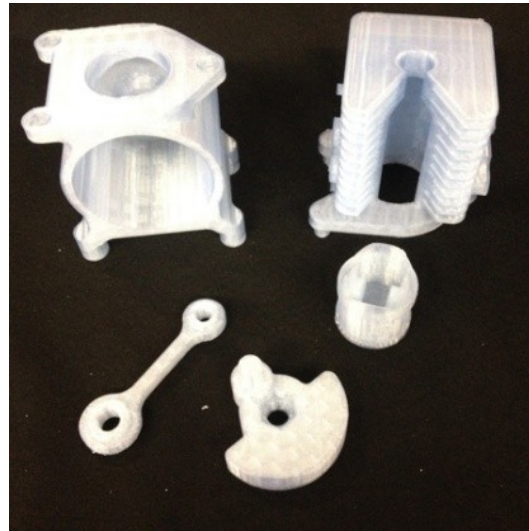
Figure 15. Parts for a Single-Cylinder Engine

Quality Control and Reliability

Standard 3D parts (20mm cubes) printed by different 3D printers in Engineering of Manufacturing Processes lab are used to verify the precision of 3D printing methods. Figure 16 shows some of the printed cubes.

Table 4 shows a dimensional analysis of 20mm cubes (shown in Figure 16) printed using the 3D-printing lab printers. While both 3D printer companies claim resolution of 0.1mm (Replicators) and 0.15mm per layer (UP Plus 3D printers) the test results shown below do not fully support those claims. Errors in the Z direction (shaded cells in Table 4) are greater than 0.1mm for Replicators.

Table 4. 20mm Cube Dimensional Tests

Material	3D Printer	20 mm Cube	Dimensions (mm)			Error (mm)		
			x	y	z	x	y	z
PLA	Replicator 2	White	19.7358	19.9034	20.0152	0.2642	0.0966	-0.0152
PLA	Replicator 2	Translucent 1	19.7053	19.8603	19.9949	0.2947	0.1397	0.0051
PLA	Replicator 2	Translucent 2	19.6977	19.9720	20.2362	0.3023	0.0280	-0.2362
PLA	Replicator 2	Translucent 3	19.6850	19.9746	20.1879	0.3150	0.0254	-0.1879
PLA	Replicator 2	Orange	19.7002	19.9949	20.1320	0.2998	0.0051	-0.1320
PLA	Replicator 2	Green	19.7104	19.8704	20.0076	0.2896	0.1296	-0.0076
PLA	Replicator 2	Blue	19.6850	20.0203	20.0177	0.3150	-0.0203	-0.0177
ABS	Replicator 2X	White	19.7256	19.7739	19.7536	0.2744	0.2261	0.2464
ABS	Replicator 2X	Orange 1	19.7256	19.7739	19.9441	0.2744	0.2261	0.0559
ABS	Replicator 2X	Orange 2	19.7129	19.7155	19.9898	0.2871	0.2845	0.0102
ABS	UP! 3D	White 1	19.7383	20.0203	19.9898	0.2617	-0.0203	0.0102
ABS	UP! 3D	White 2	19.6850	19.9644	20.0279	0.3150	0.0356	-0.0279
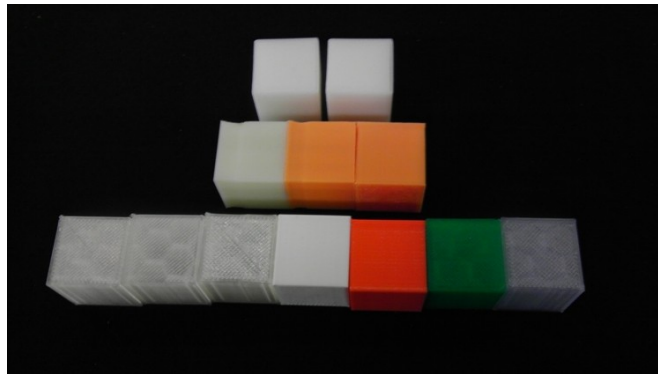
Figure 16. Cubes used in the Dimensional Test

Engineering of Manufacturing Processes

In this course students use SolidWorks and Makerware to design and/or download objects. They learn additive manufacturing and how to create mold patterns. Figure 16 shows cubes created in the associated lab. Also, Figure 17 shows one side of the thunderwolf mold pattern used for a subsequent aluminum casting lab. The casting with a downsprue, two risers, and the gating system as well as the final product casted in aluminum are shown in Figure 18.

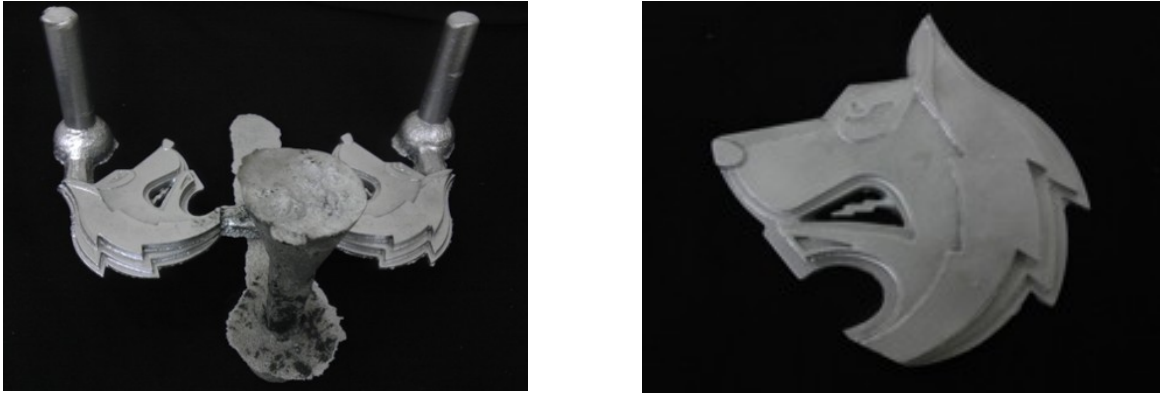

Figure 17. Thunderwolf Mold Pattern (one side)

Figure 18. A Complete Casting and the Final Product in Aluminum

Computer-Integrated Manufacturing

In Computer-Integrated Manufacturing course, apart from building their own objects as shown in Figure 19, students compare a 3-axis CNC Mill with MASTERCAM (task object shown in Figure 20) and a 3D printer with Makerware in creating comparable plastic objects. Three sample parts, one machined on a CNC mill, one created on the 3D printer (having the same dimensions as the CNC machined part), and one 3D-printed improved part are shown in Figure 21.

Figure 19. Student-built Objects
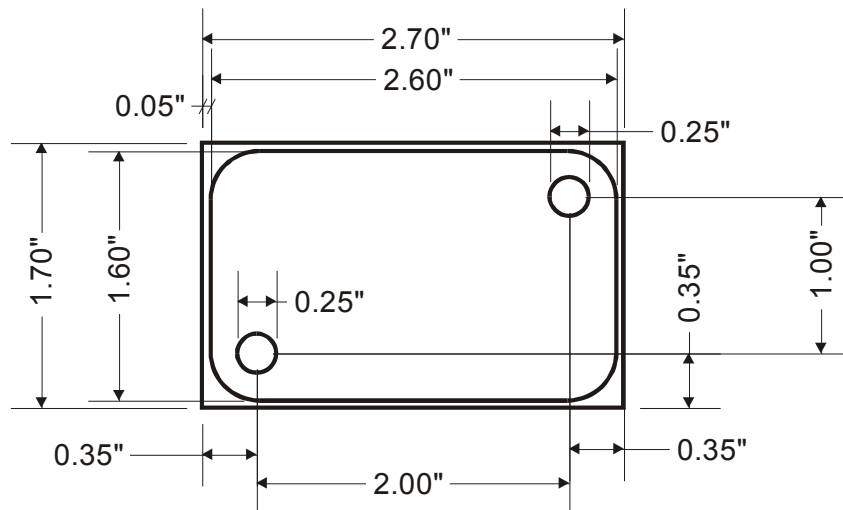
Figure 20. CNC Task: a Key-chain Workpiece with Rounded Edges and Two Holes
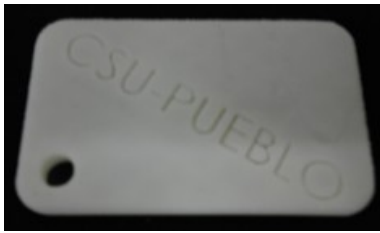
CNC Key-chain   3D-printed Key-chain   3D-printed Improved Key-chain

Figure 21. Comparison of CNC and 3D-printed Parts

Controls I and II

In the lab component of this course students build and control planar 2-degree-of-freedom robots. Figure 22 depicts one such project with many plastic parts created by using SolidWorks and Up Plus 3D printer.
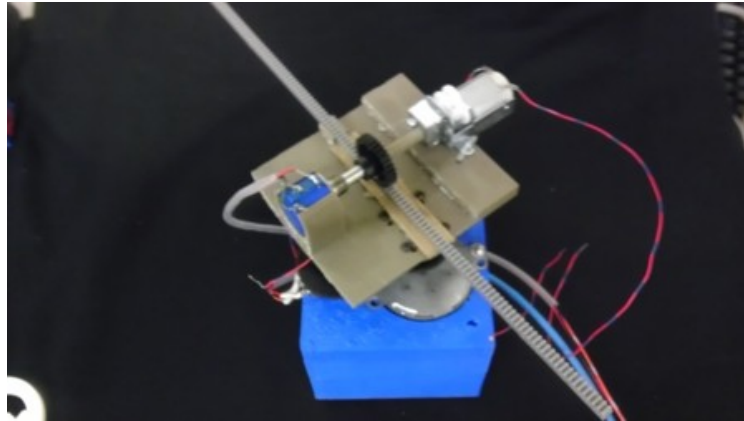

Figure 22. Planar Robot for the Controls Class

Student Projects

Engineering design courses like independent projects or senior design projects emphasize the use of SolidWorks coupled with 3D printers to build working prototypes. Figure 23 depicts a quadcopter that was adapted from a design found on www.thingiverse.com. Parts were printed in ABS on Up Plus 3D printer. The legs had to be printed in two pieces due to the build-volume limitations of the 3D printer.
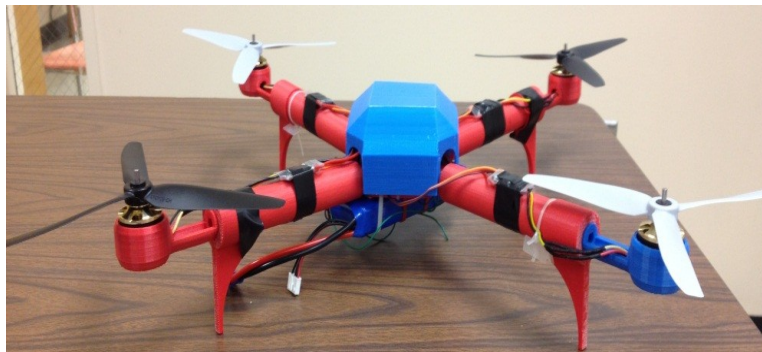
Figure 23. 3D–printed Quadcopter

Another large student project involved a new low-cost design for an atomic force microscope (AFM). A number of parts were created using one of the UP Plus 3D printers. Figure 24 shows one of the design iterations in ABS designed in SolidWorks and printed by an UP Plus 3D printer. The model was used to test for assembly fit of other parts: a computerized microscope, an xy-table, and a photo-detector with electronics.
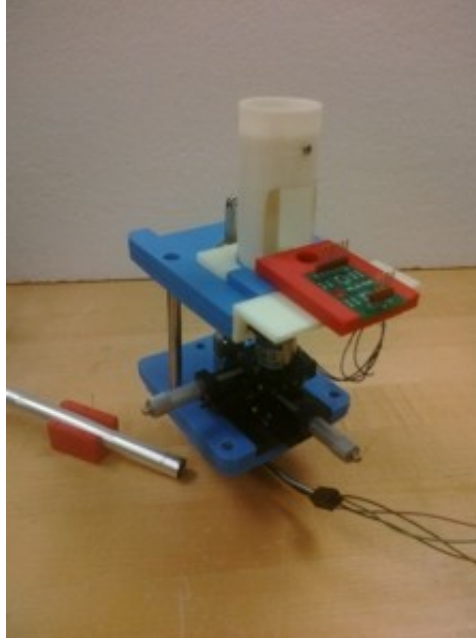

Figure 24. Atomic Force Microscope Design in Plastic

Physics

While this is not realized yet, a Wave function will be created and then printed by using one of the 3D printers.

Non-Engineering Implementations

Engineering students and the student lab assistant printed a number of objects not directly related to any of the engineering labs. This was encouraged by the professor in charge, so that the students would embrace the 3D-printing technology. In one case, a student from psychology came to us so that we could build a large cube for her. The cube was to be used for educating individuals with learning problems. A tactile feedback was required to help them memorize some facts easier. The first iteration of the cube (she provided the SolidWorks files) didn't' work well so our engineering students redesigned the cube to fold and unfold easier. Figures 25 and 26 are photographs of the cube.

Table 5 shows 3D printer uses for other non-engineering curriculum activities. For Biology we download and printed a myovirus bacteriophage and a trilobite as shown in Figure 27. Figure 28 shows some interesting objects that students printed last semester.
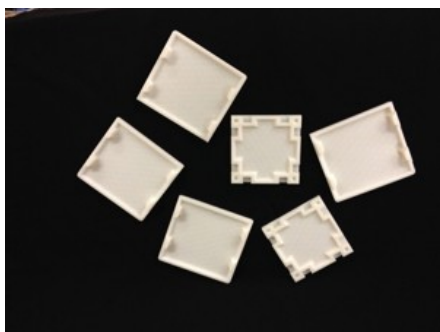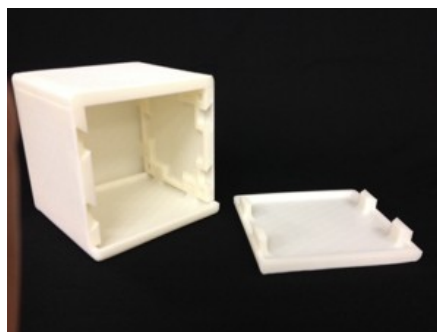
Figure 25. Redesigned Cube (parts)

Figure 26. Redesigned Cube (Mostly Assembled)

Table 5. Non-Engineering Curriculum Applications

| Department/Program	Objective	Object	Cost ($)
Civil Engineering Technology	Demonstration	House	5.00
Automotive Industry Mgmt	Visualization	Gear Bearing	1.04
Mathematics	Visualization	"Peaks"	0.82
	Visualization	Toroid	1.00
Biology (in process)	Visualization	Bacteriophage	<1.00
Chemistry (in process)	Visualization	Small Molecule	<1.00
Library (their Printer)	Applications	Various Designs	NA
Outreach Activities	Demonstration	Bracelet	0.22
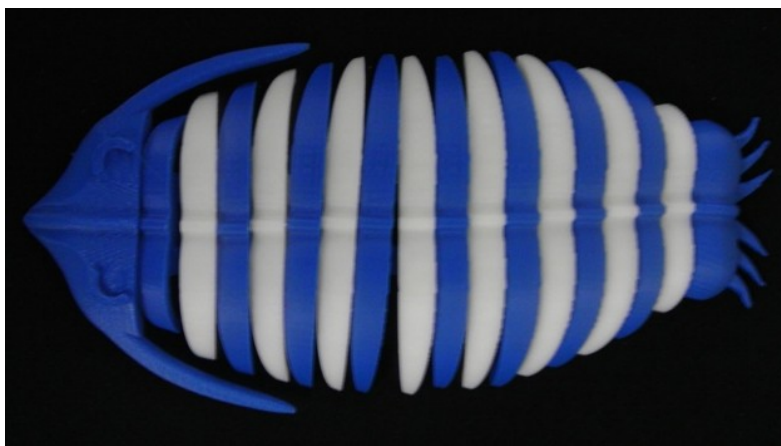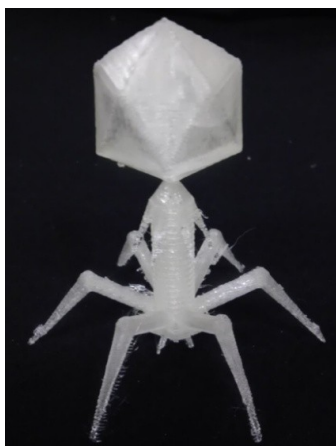
Figure 27. Myovirus Bacteriophage and Trilobite

Our library staff have applied for an internal grant to buy three additional 3D printers for use in our university library. We are working with them to increase the number of 3D printers on campus. Engineering will provide a student 3D-printing lab assistant for the library.

As part of our outreach activities with K-12 students, MakerBot Replicator 3D printers are used to create bracelets downloaded from www.thingiverse.com. The bracelets show how easy it is to print 3D objects when they are already provided in a correct file format. Bracelets are chosen because they can be printed in about 20 minutes during our outreach activities.
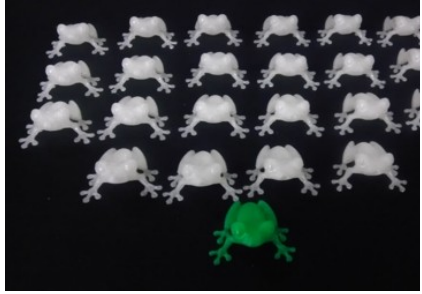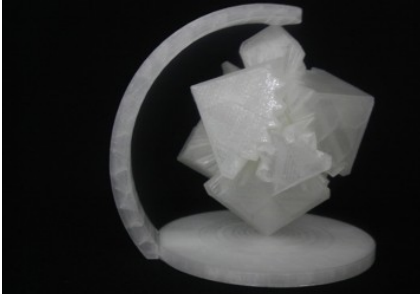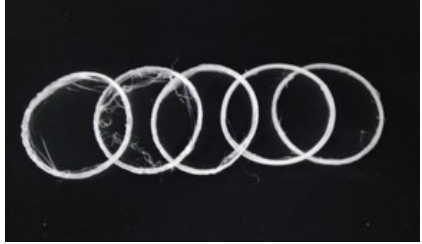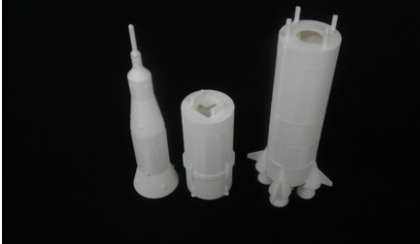
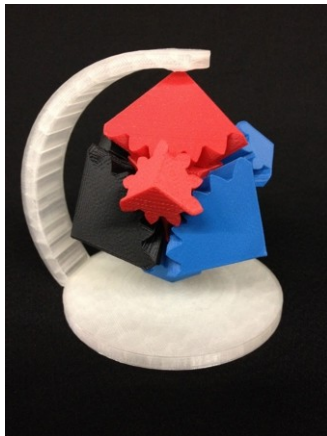| Frogs	Gears in Motion 1	Chocolate Bunny with Mold

Flexible Rings	Rocket Parts	Dragons, Thunderwolf, and TARDIS
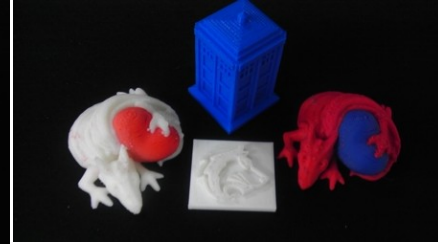
Gears in Motion 2	Rocket - Assembled	Lamp

TARDIS with Lights	Halloween Decorations	House

Figure 28. Some Interesting Objects Created in the 3D-Printing Lab

Assessment and Evaluation of Student Learning and Engagement

Students were active participants in the creation of the 3D-printing laboratory through their input in writing a university-wide grant proposal for the 3D printers. They concluded that the one small working 3D printer that the institution had at that time was not sufficient for their projects nor was it adequate for learning this exciting technology.

The disciplinary knowledge of 3D-printing technologies is assessed in courses like Engineering of Manufacturing Processes and Computer-Integrated Manufacturing (CIM) through course exam questions and mandatory labs. In general, pre- and post-tests show a considerable increase in students' knowledge of 3D-printing technologies. Successful completion of assigned lab assignments shows students' proficiency with 3D printers. For the manufacturing course, the last school-year when the department only had one 3D printer, students were exposed to 3D printing through a demonstration. Independent printing of parts for other courses and/or uses was voluntary. Students printed few parts found on the Web and two groups of students designed and printed parts for their Controls lab. The last semester, in the CIM lab all students had to print something. About half of them decided to print an object from http://www.thingiverse.com/, while the other half designed their own objects ranging from Toyota symbol for a truck to TARDIS from Dr. Who TV series. A lab on direct comparison of parts created by a CNC tool mill and comparable 3D-printed parts was conducted.

However, the proof of students' engagement with and acceptance of the 3D printing technology is the number of objects created and the success of students' independent projects and senior design projects which included some (or all) 3D-printed parts. In the last six months, the 3D-printing lab printed over 800 objects, used over 20 kg of plastic, and logged over 1200 printing hours for the seven 3D printers. Students completed a number of projects including a robot for an IEEE robotics competition, a robot for a NASA-supported robotics competition, a quadcopter (modified from an existing design), a plastic removable cast for a broken arm, and an atomic force microscope (AFM) where most of the 3D-printed AFM parts were used in the preliminary stages of the design. This semester, all mechatronics students used 3D printers to some extent in their senior design projects for designing and creating functional parts.

Summary

This paper provided justifications for using 3D-printing technologies in undergraduate engineering education. Creation of functional parts in the first year of study by various engineering majors, quick verification of designs early in the curriculum, fast turn-around times from "imagination to implementation," the decreased need for students with the well-developed machining skills, connections with other sciences and mathematics through 3D built objects, and increased lab safety are powerful benefits of this technology.

A number of applications of inexpensive FDM 3D printers in two multidisciplinary engineering programs encompassing a number of engineering courses are illustrated in detail to encourage and enable other engineering education practitioners to implement 3D printers in their courses and programs. The advantages of the FDM 3D printing technology as compared to other 3D printing technologies are noted. A set of 3D-printing laboratory policies and procedures implemented in a successful 3D-printing laboratory are reported. A number of parts ready for implementation in various engineering and non-engineering courses are provided. Students' proficiency and acceptance of the 3D-printing technology are measured quantitatively through a number of 3D-objects created (over 800), and qualitatively through the types and complexity of

the objects printed (objects and assemblies downloaded from the Web, objects modified from the Web, reverse-engineered objects using CAD drawings, and entirely novel designs). The students' engagement with the 3D-printing technologies was high since a good portion of students designed their own objects. Some students used 3D printers to build parts for their independent studies, special projects, and senior design project classes.

Integration of 3D-printing technology in engineering education may have far-reaching implications. Apart from contributing directly to the ABET student outcomes (c) and (k) and the Kolb's experiential learning cycle, 3D printers may heighten students' intellectual curiosity and grit, thus improving students' chances of success in engineering.

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