ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #16253

MAKER: 3-D–Printing Evolution in Engineering Education: The Things We Make

Prof. Nebojsa I. Jaksic, Colorado State University, Pueblo

NEBOJSA I. JAKSIC earned the Dipl. Ing. degree in electrical engineering from Belgrade University (1984), the M.S. in electrical engineering (1988), the M.S. in industrial engineering (1992), and the Ph.D. in industrial engineering from the Ohio State University (2000). He is currently a Professor at Colorado State University-Pueblo teaching robotics and automation courses. Dr. Jaksic has over 60 publications and holds two patents. Dr. Jaksic's interests include robotics, automation, and nanotechnology engineering education and research. He is a licensed PE and a member of ASEE, IEEE, and SME.

MAKER: 3D-Printing Evolution in Engineering Education: The Things we make

Abstract

This paper presents the five stages of evolution in the inexpensive 3D printing movement by defining and measuring the degree of acceptance/usefulness of inexpensive 3D printing technologies in an engineering educational environment. The stages (Familiarization, Design, Extension, Material Exploration, and Expansion) are defined as a function of quality and quantity of students' involvement through the degrees of complexity, ingenuity, and utility of printed objects, as well as the students' sophistication in using additional machines and techniques supporting 3D printing processes. A number of examples from an engineering department's 3D printing laboratory are provided to illustrate the various stages of 3D printing evolution.

Introduction

Experiments and other hands-on activities are well-known cornerstones of education and are highly supported by the experiential education philosophy established by Dewey[1], and the experiential learning cycle developed by Kolb[2]. Designs, physical models, and prototypes are accepted as an integral part of engineering education in both education research[3-5] and engineering curricula[6, 7]. Furthermore, engineering texts address 3D printing technology[8] and practice[9].

The 3D-printing revolution is here. New inexpensive 3D printers are introduced weekly. Universities, two-year colleges, and K-12 institutions are buying 3D printers for their design courses. Many of the middle schools and high schools in the country already have at least one 3D printer. Technology enthusiasts belonging to the Makerspace movement often use communal space equipped with multiple 3D printers, laser cutters/engravers, and CNC machines. While the 3D printers based on fused deposition modeling (FDM) are still prevalent, other inexpensive 3D-printing technologies are slowly gaining acceptance among builders. Also, pre- and post-processing tools and techniques are being developed at an increased pace.

The engineering department's 3D-printing lab at our institution is used primarily by undergraduate engineering students (mechatronics and industrial engineering) for mechanical designs in various courses and in support of technical extracurricular activities. It includes ten inexpensive 3D printers with pre- and post-processing tools and employs two half-time student technicians. Some facets of the 3D-printing lab are described elsewhere[10-12].The described lab experiences are based on over five thousand print-time hours and over two thousand printed objects ranging from Thingiverse bracelets to sophisticated multi-part assemblies of students' own designs. In this work, an evolution in printing practices is described and viewed through a prism of objects printed. This work categorizes 3D printed objects as students move through different evolutionary stages while they become more experienced and engaged with 3D printing technologies. The stages are addressed in the following section.

Five stages of 3D printing evolution

In this work, the development of 3D printing knowledge and expertise is categorized in five evolutionary stages as shown in Table 1.

Table 1. The five stages of 3D printing expertise evolution

Stage	Name	Characteristic
Stage 1	Familiarization	Manufacturer supplied and web-based objects printed
Stage 2	Design	Student-designed (CAD) objects printed
Stage 3	Extension	Pre- and post-processing tools used
Stage 4	Material Exploration	Materials beyond ABS and PLA explored
Stage 5	Expansion	New 3D printing technologies/equipment researched

Stage 1: Familiarization

At the Familiarization stage, after the 3D printers are assembled and the slicing software installed, students print test objects supplied by the 3D printer manufacturer. Then, they download project files from the Web (e.g. Thingiverse) and print some of the objects. As the students become more proficient they print more complex objects and assemblies. This stage also includes the development of skills dealing with 3D printer platform calibration, filament changing, object removal from printers, object clean up, and nozzle maintenance. Also, students gain experience with printing platform preparation including the use of Kapton tape, acetone/ABS (acrylonitrile butadiene styrene) mix, or hairspray when using ABS filament, as well as paper tape, glass, or paper glue when using PLA (polylactic acid) filament.

Figure 1 depicts typical objects printed at this stage as well as some of the tools used. Figure 1-a shows a set of bracelets printed in PLA. Even though PLA is not flexible, due to their geometry the bracelets are. Figure 1-b presents an assembly. Multiple parts are printed separately and then assembled into a final product. Each elephant in Figure 1-c is an assembly where all the parts of the elephant are printed simultaneously. After an elephant is released, the legs (in pairs) and the head can move independently allowing the elephant to be placed in different positions. Figure 1-d[13] presents some tools used in object removal and cleaning of the support material. Spatulas, pliers, woodcarving tools, scissors, files, etc. can be used for this purpose. In some cases, the material used for the support structure is dissolvable. Here, students immerse objects into an acid solution to clean the parts. However, the dissolvable support material technique is somewhat cumbersome, slow, and expensive.

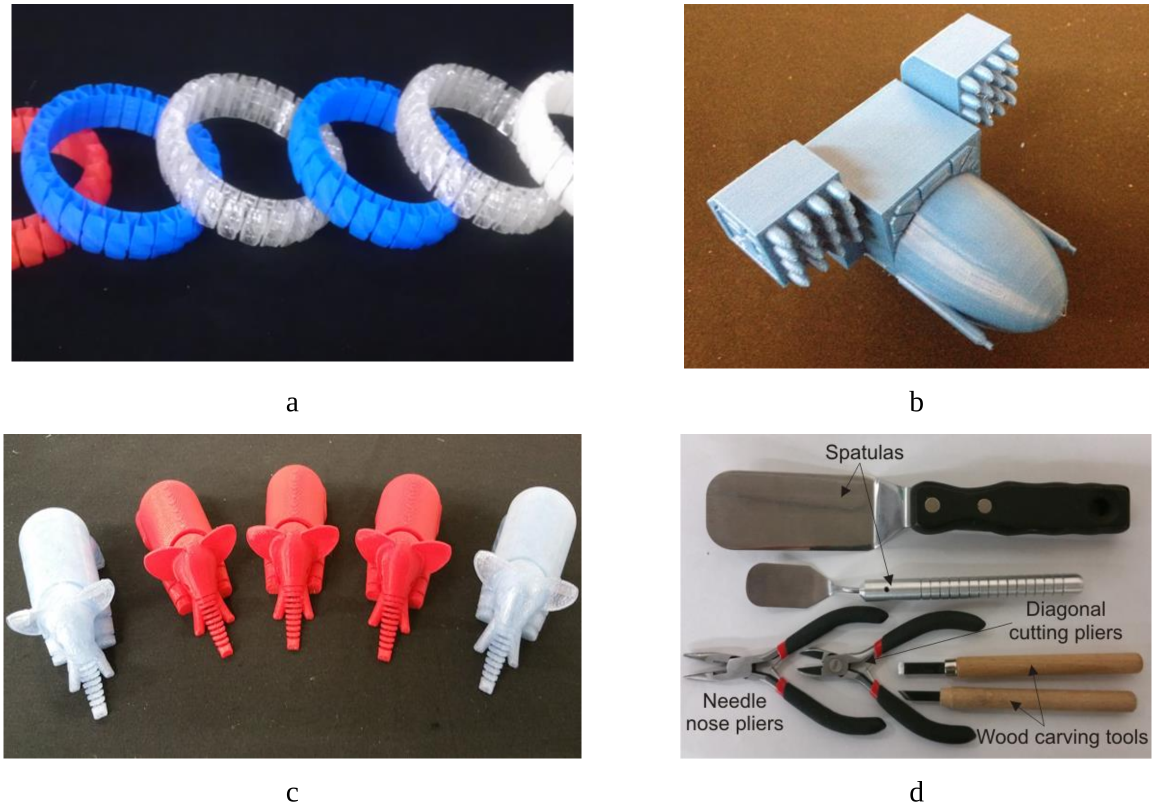


Figure 1. Familiarization stage objects and tools: a) stretchable bracelets, b) missile platform assembly, c) elephants, d) object removal and cleaning tools[13]

Stage 2: Design

In the Design stage students start using CAD (Computer-Aided Design) software to create their own objects. At the beginning of this stage, the objects are usually already existing parts or objects that are easy to visualize such as robotic wheels, enclosures, small personalized objects like key chains, modified objects from the Web, etc. After this, students may print 3-dimensional mathematical curves and start with more complex objects. At the end of this stage students design and print whole mechanical assemblies like robotic platforms, prosthetic hands/arms, and other new designs including art. Also, students learn best practices in 3D printing when dealing with the selection of materials (ABS or PLA) and colors (not all colors print equally), clogged nozzles, object designs for 3D printing, object placement and orientation, and 3D printing process parameters such as temperature, speed, fill, rafts, etc.

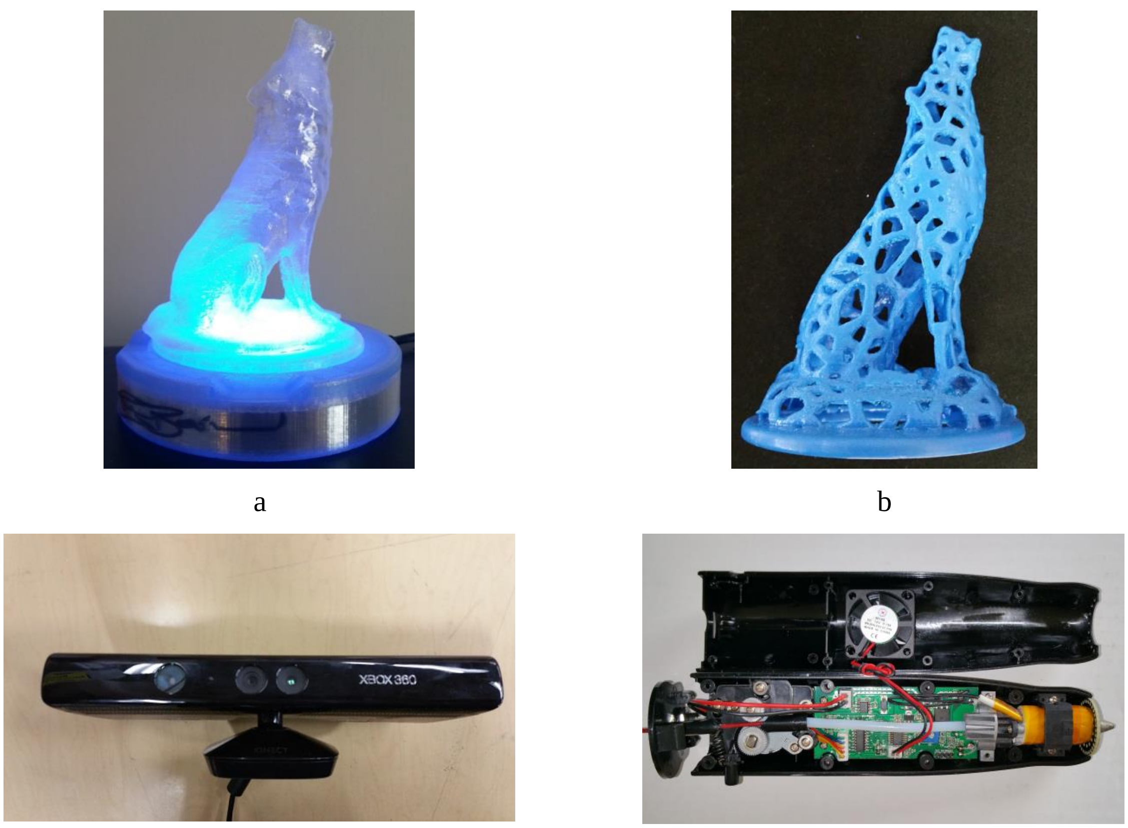
Figure 2 shows objects exemplifying the Design stage. Figure 2-a depicts a set of about 60 key chains designed and printed for an IEEE student section outreach event. Figure 2-b pictures 3D printed Christmas tree decorations, some designed by students and some downloaded from Thingiverse. This was a part of a fund-raising auction for a local Boys and Girls club. Figure 2-c is an example of using a mesh function in CAD and 3D printing the resulting object – a cup. Figure 2-d is a plastic model of an AFM (atomic force microscope) used to validate assemblies. Figures 2-e and 2-f depict two inventions in their proof-of-concept stage.

Figure 2. Design stage objects: a) a set of key chains, b) Christmas tree ornaments, c) CAD cup, d) AFM plastic prototype[10], e) Rotating part of a toy invention, and f) Plastic arm cast invention

Stage 3: Extension

In the Extension stage students use pre- and post-processing tools and techniques to create their objects, repair failed prints or to create larger assemblies. As a pre-processing step, students learn how to use 3D scanning hardware platforms with associated software (e.g. Kinect sensors with Skanect software or Next Engine 3D scanner). Some examples of post-processing tools and techniques are 3D pens, soldering irons, Dremel rotating tools, sandpaper, and acetone[13, 14]. These tools are used to enhance 3D printed objects.

Figure 3-a depicts a student-designed smart lamp with a wolf lamp shade. The shade is a scanned replica of a life-size bronze statue placed outside the university printed in a special way to allow the light from the lamp to pass through. The smart lamp has two capacitive sensors acting as two switches that allow changes in color and light intensity of the lamp. Figure 3-b is the lamp shade created from the same scan, but is a result of experimenting with mesh CAD functions. Xbox 360 Kinect, as depicted in Figure 3-c, is the students' choice in scanning. The device creates usable scans (especially of people) quickly, is easy to use, and is inexpensive ($30-$50). The Next Engine 3D scanner is capable of much higher scanning resolution, but it is slow (scans may take hours) and it is more expensive ($2,000-$4,000). Figure 3-d depicts a 3D pen, a device that can be used in rework or assembly post-processing operations. Basically, it is a hand-held plastic extruder that uses the same plastic filament as 3D printers. When the start button is pressed and held, the 3D pen's motor pulls the filament in. As the filament travels towards the nozzle it passes through a heated area, melts and is extruded through the nozzle.



a b c d

Figure 3. Extension stage objects: a) Scanned wolf smart lamp, b) CAD modified scanned Wolf, c) Kinect scanner, d) 3D pen

Stage 4: Material Exploration

In the Material Exploration stage, students start exploring different printing materials available in addition to ABS and PLA to create objects with different characteristics (e.g. electrical, magnetic, and mechanical). This stage further fosters students' creativity and leads them towards materials research. Students usually start with flexible filament or glow-in-the-dark filament (not counting dissolvable material used as support). Then they progress through different nylons, and then they start exploring various composites (iron, steel, tungsten, graphite, graphene, wood, etc.). Figure 4-a depicts some advanced materials. Graphene/PLA composite can make 3D printed objects conductive. Applications of advanced 3D printing materials are active research areas. For example, Figure 4-b depicts experimental studies of conductive materials (graphene-based and carbon black-based) for use in resistor circuits.

a

b

Figure 4. Material exploration materials: a) advanced 3D printing plastic and composite materials and b) testing of conductive materials as resistors

Stage 5: Expansion

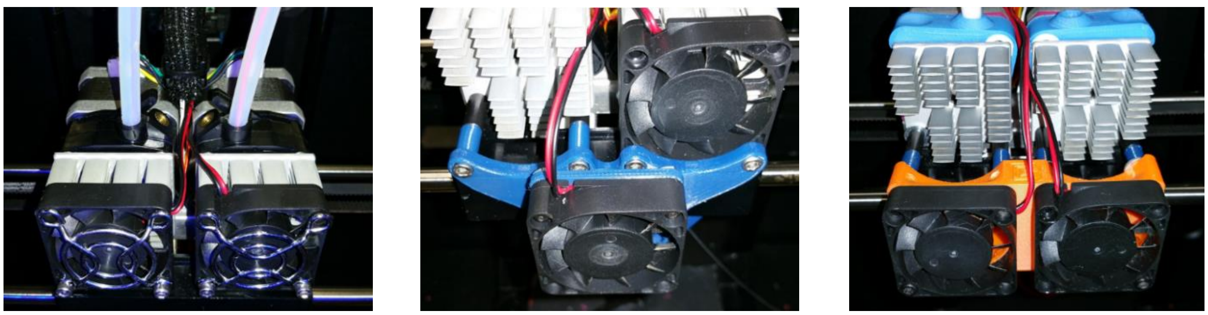
In the Expansion stage students start testing other inexpensive 3D printing technologies such as SLA DLP (stereolithography digital light projector) 3D printing or metallic clay 3D printing (capable of creating metal parts), as well as, they start modifying 3D printers and/or add new equipment to supplement 3D printing labs (like a recycling system).

Example 1. In the Expansion stage students investigate new inexpensive 3D printing technologies using materials such as UV-curable resin or metallic clay. Table 2 shows a quick comparison between traditional FDM (fused deposition modeling) 3D printers like MakerBot Replicator 2X which can print using two filaments, and two recent entries: Pegasus Touch which implements the SLA DLP technology and uses FSL3D (Full spectrum laser) UV-curable resin, and Mini Metal Maker that implements FDM to deposit special metal clay that is then fired in an oven. The speed of part production for each of these printers requires further clarification. For Replicator 2X, most of the time in creating a part is due to printing. Usually, only a few minutes are required for part removal and cleaning. Pegasus Touch prints extremely fast. However, curing of such printed parts may require hours. Mini Metal Maker deposits clay as quickly as other FDM printers. However, to create a metal part the as-printed part must undergo a firing cycle that also lasts hours. Precision of created parts depends on the technology and materials used.

Table 2. Comparison of three inexpensive 3D printing technologies

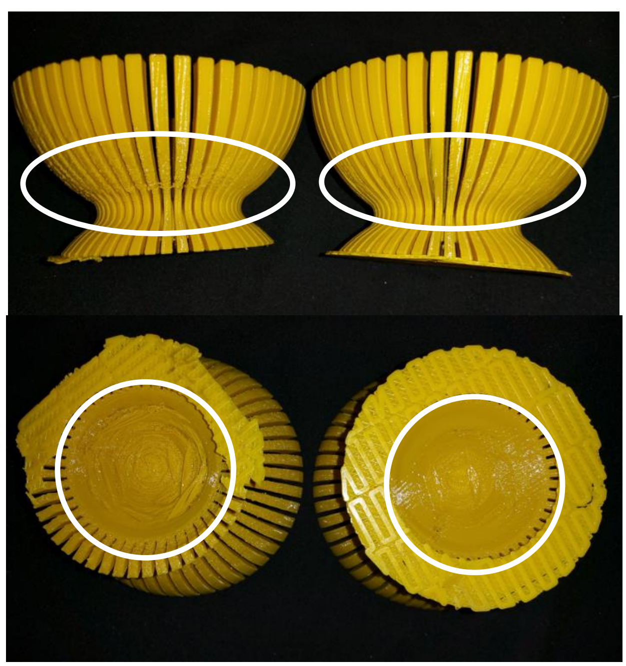
Name	Technology	Price	Material	Price/Mat	Resolution	Speed
MakerBot Replicator 2X	FDM	$2500	ABS, PLA	$50/kg	100 μm	varies
Pegasus Touch	SLA DLP	$3000	FSL3D resin	$138/kg	50 μm	1s/layer
Mini Metal Maker	FDM	$2300	Metal Clay	$200/kg	100 μm	varies

Example 2. Figure 4 shows MakerbBot Replicator 2X 3D printer improvements by adding extra fan(s). Figure 4-a shows the 3D printer extruders as purchased, Figure 4-b depicts a single fan added to the extruders, while Figure 4-c shows two fans added to the extruders blowing air at the nozzles. Figure 5-a shows a part printed before changes, while Figure 5-b shows improved prints.



a b c

Figure 4. Replicator 2X improvements: a) as purchased, b) extra fan, and c) two extra fans

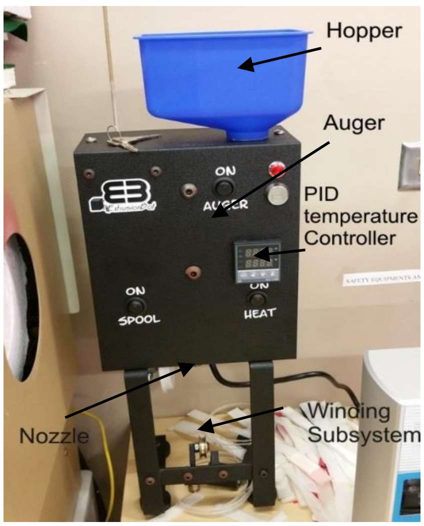


a b

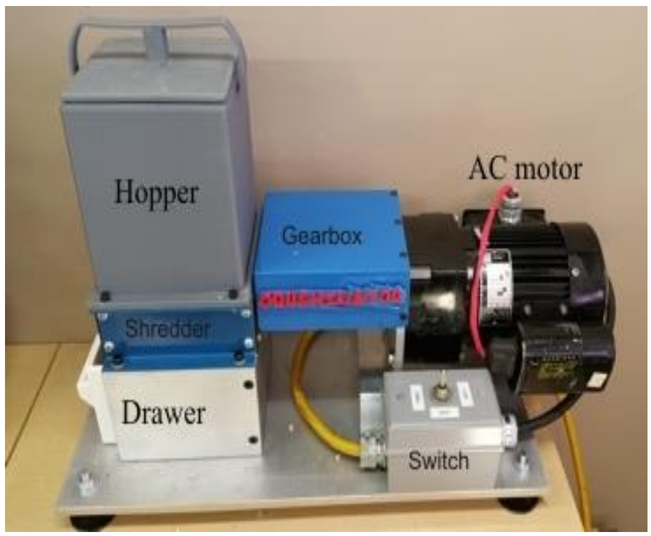
Figure 5. 3D printed part: a) before and b) after the 3D printer modification

Example 3. Figure 6 shows the recycling system developed for the engineering 3D printing lab[12]. Figure 6-a pictures a filament extruder made by ExtrusionBots. The extruder is a desktop device consisting of a hopper, auger, heater including a PID (Proportional Integral Derivative) temperature controller, nozzle, and an automated winding subsystem. The filament extruder accepts small granules which are fed into the hopper. The granules are transported to the heating chamber via the auger. When the temperature of the chamber reaches a preset temperature value (programmed via the PID temperature controller) the filament is extruded through the nozzle. The automatic winding subsystem consists of a spool, spool motor, fan, two optical interrupt sensors, some digital electronics and a relay. During the extrusion process, an operator manually winds some filament onto the spool to get the process started. Then, when the filament triggers optical sensors, indicating that filament is between the two sensors, the spool motor starts and winds the filament onto the spool. The filament tension is measured by the two sensors and regulated by the spool motor and a relay. The extruder produces filament ready for use in 3D printers.

Figure 6-b depicts a motorized desktop plastic shredder developed around a manual shredder mechanism purchased from FilaMaker. These two pieces of equipment allow students to mix virgin and recycled material in creating their own filament as they explore material characteristics.



a



b

Figure 6. Expansion stage equipment[12]: a) Filament extruder and b) Plastic shredder

Culture Change

All undergraduate engineering students are required to use 3D printers in many of their courses. Individual interviews with a number of students addressed questions about the usefulness of 3D printing technologies. Our results show that students show great enthusiasm for 3D printing technologies and through years of use they develop expertise.

A new engineering design culture has emerged. It revolves around the 3D printing lab which became a crucial element in required courses, special projects, independent studies, senior project design courses, master thesis research, as well as, events supported by student sections of engineering societies (IEEE and IIE), and community events. Funding from the University and the Department of Engineering enabled this cultural change by supporting two half-time undergraduate student technicians, 3D printers, 3D printing material, and the lab facilities. The departmental policy where all students can use 3D printers free of charge further incentivized the printers' use.

Summary

This work defined five stages of 3D printing evolution: Familiarization, Design, Extension, Material Exploration, and Expansion. An undergraduate engineering 3D printing lab consisting of ten inexpensive 3D printers, two scanners, three 3D printing pens, and a novel recycling system was used to provide examples for each of the five stages. A positive culture change towards engineering designs and engineering as a whole was noted.

Acknowledgment

The author gratefully acknowledges Paul Wallace, Tim Roush, and Brian McKimson for their contributions in plastic shredder design, as well as Pratik Desai for his contribution to 3D printer modifications and the conductive filament example.

Bibliography

1. Dewey, J., *Experience and Education*, Macmillan, N.Y., 1939.
2. Kolb, D. A., *Experiential Learning: Experience as the Source of Learning and Development*, Prentice Hall, Englewood Cliffs, N.J., 1984.
3. Schmucker, D. G., "Models, Models, Models: the Use of Physical Models to Enhance the Structural Engineering Experience," *1998 American Society for Engineering Education Annual Conference and Exposition Proceedings*, Seattle, WA, June 28-July 1, 1998. Session 3615
4. Viswanathan, V. K. and Linsey, J. S., "Build to Learn: Effective Strategies to Train Tomorrow's Designers," 2012 *American Society for Engineering Education Annual Conference and Exposition Proceedings*, San Antonio, TX, June 10-13, 2012. AC 2012-4896
5. Nagel, R. L., Pierrakos, O., and Nagel, J. K., "A Versatile Guide and Rubric to Scaffold and Assess Engineering Design Projects," *2013 American Society for Engineering Education Annual Conference and Exposition Proceedings*, Atlanta, GA, June 22-26, 2013. Paper ID #7298
6. Ullman, D., *The Mechanical Design Process*, 4th edition, McGraw-Hill, 2009.
7. Dieter, G. and Schmidt, L., *Engineering Design*, 5th edition, McGraw-Hill, 2012.
8. Groover, M. P., *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, 5th edition, Wiley, 2012.
9. Planchard, D. C., *Engineering Design with SolidWorks 2015 and Video Instruction*, SDC Publications, Mission, KS, 2015.
10. Jaksic, N., "Novel Experiential Learning Practices in Engineering Education Based on Inexpensive 3D Printers," *Computers in Education Journal*, Vol. 5, No. 4, pp. 2-17, October-December 2014.
11. Jaksic, N., "When 3D-printers go Wrong: Laboratory Experiences," *2015 ASEE Annual Conference and Exhibition*, Seattle, WA, June 14-17, 2015.
12. Jaksic, N., "Sustainable Undergraduate Engineering 3D Printing Lab," 2016 ASEE Annual Conference and Exhibition, New Orleans, LA, June 26-29, 2016. (in print)
13. Jaksic, N., "Post-processing 3D-printed Plastic Objects: Laboratory Tools, Techniques, and Experiences," *2015 ASEE Rocky Mountain Section Conference*, Denver, CO, pp. 27-34, April 10-11, 2015.
14. Jaksic, N., "BYOE: Using 3D Pens for Enhancement and Rework of 3D-Printed Parts," *2015 ASEE Annual Conference and Exhibition*, Seattle, WA, June 14-17, 2015.