The RepRap 3-D Printer Revolution in STEM Education

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Next Generation Science Standards

STEM is an acronym for science, technology, engineering and mathematics fields of study meant to improve U.S. competitiveness by guiding curriculum and influencing education policy. STEM education begins with K-12 educators, who are struggling with how to implement the Next Generation Science Standards (NGSS) that now place explicit emphasis on the relationship of engineering to science. The NGSS guidelines suggest that science curriculum should have activities with an iterative process involving; defining the problem, developing possible solutions, and optimizing design solutions. The NGSS guidelines for K-12 science education are present at all grade levels at varying degrees. Implementation of these guidelines are present in the Museum of Science in Boston's Engineering is Elementary where engineering design is embedded in materials that can be used for both science and language arts for the elementary grades.[1]

The NGSS guidelines include a framework with eight practices including number six, "constructing explanations and designing solutions", which is where one major distinction is made between science and engineering practice. The goal of science is to construct theories about the natural world where the goal of engineering design is to find solutions to problems that can be manifested in a physical product, plan, or mechanical device. K-12 student practices for number six require using tools and materials to build a device that solves a specific problem, with 9-12 requiring more sophisticated projects involving design, constructing and/or testing a design of an object, tool, process, or system.[2]

K-12 science education will find it increasingly necessary to implement practices from vocational, occupational, and/or industrial technology to fully implement the NGSS framework. Concern for proper safety precautions, limited access to resources, and lack of professional development of science educators may prohibit these activities. Even though just a handful of states have officially adopted the NGSS standards, the National Science Teachers Association (NSTA) called for states to adopt NGSS in the November 2013 publication "Position Statement" that outlines the steps needed to ensure all students have the skills and knowledge required for STEM careers and includes teacher professional development.[3]

Engineering Design Process

The NGSS core ideas of "Engineering, Technology, and Applications of Science" are infused in college level Engineering Technology (ET) curricula as the "Engineering Process" or "Design Process" and are typically introduced early on, and then generally put into practice during capstone project courses. ET faculty and high school science teachers are required to develop projects where students experience real-world examples of design-build-test that can be completed in one or two semesters inexpensively and with tangible results. Engineering technology baccalaureate degree program must provide a capstone or integrating experience that develops student competencies in applying both technical and non-technical skills in solving problems (as specified in the ABET ETAC general criterion 5: curriculum).[4] An example of this need is expressed in one of the recommendations from the ASME Vision 2030 report where the current weaknesses of graduates expressed by their employers, as well as the early career engineers themselves are that Mechanical Engineering Technology (MET) programs should strive towards creating curricula that inspire innovation, creativity, and entrepreneurship and that Mechanical Engineering (ME) programs should include an increased emphasis on practical applications of how devices are made and work.[5] The ASME Vision 2030 report states that:

> *"To address these weaknesses, an increase in and enrichment of applied engineering design-build experience throughout degree programs is urged."*

Product design and development tasks, sometimes referred to as product realization steps, are outlined in many college texts (for example in "Engineering Design" by Dieter and Schmidt [6]) distinguishing conceptual design, embodiment design and detail design. Testing usually takes place during the embodiment design phase, requiring models, simulations, and in certain circumstances physical prototypes to optimize the design. While research studying the effect of rapid prototyping in the design process [7,8,9] for practicing engineers and industrial designers has been completed, literature regarding the effectiveness of rapid prototyping in teaching and learning the design process is lacking.

Prototypes can take several forms; for instance a model created from readily available items such as a toothpick bridge, to a fully functional model of the lunar rover permitting testing of its operation prior to sending it into outer space. Prototype parts can be created using traditional machining to remove material by cutting, shaving, and turning using a tool in contact with unfinished stock – a subtractive manufacturing (SM) process. Additive manufacturing (AM) is the process of building models in their final or near-final shapes by successive addition of the model medium. Rather than removing material, it is added in a controlled fashion until the model's shape is produced. Both manufacturing methods rely heavily on Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM).

Advantages of AM over SM include speed and cost, especially when SM involves the creation of expensive molds or dies. AM also permits the freedom of making design changes quickly without the constraints of complicated (and expensive) tooling changes.[10] One type of AM technique utilizes Computer Numerical Control (CNC) technology to guide a heated nozzle along a tool path describing thin horizontal slices of the model, while extruding plastic material which hardens upon cooling. The open source methodologies, which includes both universal access via free license to a product's design and universal redistribution of that design and all derivatives, was so successful in software development [11] that it has been applied to AM and 3D printing.[12] The subsequent advancements in both open source 3D printing hardware and related open source software has started a revolution in the availability of rapid prototyping technologies to a far larger audience than just practicing engineers and research scientists.

Desktop 3D Printers

There are many desktop 3D printers available on the market today. Desktop 3D printers can be categorized as; not assembled "DIY" open source, fully assembled open source, and commercial systems with proprietary software. Some examples of the desktop 3D printers and their respective prices are included in Table 1.

Desktop 3D Printer	DIY Open Source	Fully Assembled Open Source	Commercial	Approximate Cost
Prusa Mendel RepRap	X			$550
Delta RepRap	X			$400
Trinity Labs		X		$2,199
Aleph Objects		X		$1,725
Type A Machines		X		$1,400
Printrbot LC		X		$799
Makerbot Replicator			X	$2,800
Statasys Mojo			X	$10,000

Table 1. 3D Desktop Printers

Open source 3D printers are an inexpensive approach which educators can use to integrate the design-build-test process into science curricula even without an extensive technological background. The cost to build a Prusa Mendel version of a self-replicating rapid prototyper (RepRap) is approximately $550 for the components, including the necessary 3D-printed parts which need to be created on an existing machine. This 3D printer can be assembled in as little as two days.[13] The RepRap has already demonstrated utility in a wide range of educational environments.[14, 15] The RepRap Project has an open source hardware design using open source software with the intent to improve on the design and software with each future generation.[16] The 3D printer extrudes either polyactic acid (PLA), which most of the parts for the printer are made from, or acrylonitrile butadiene styrene (ABS) used for parts requiring high heat resistance (see Figure 1).

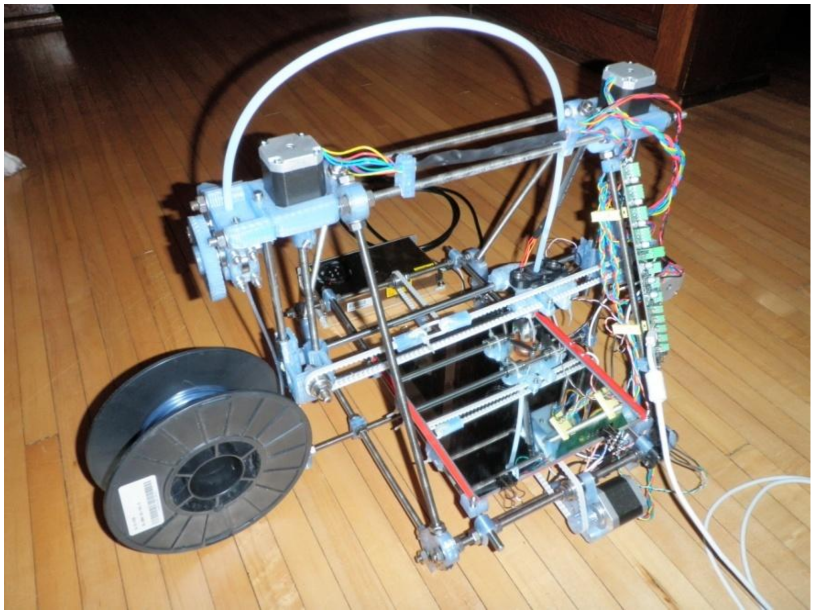

Figure 1. MOST Prusa Mendel RepRap

Teaching K-12 Teachers the Engineering Process

Two professional development courses for K-12 science teachers have been offered as part of a Master’s degree in Applied Science Education at Michigan Technological University. They were partially funded by two different Title II Improving Teacher Quality grants awarded during the 2009-10 and 2013-14 cycles. “The Engineering Process” course and “Engineering Applications in the Physical Sciences” course have each provided practicing science teachers exposure to open source 3D printing technology and techniques to implement NGSS framework practices in their classrooms. The first course is intended to introduce engineering to pre-college teachers by providing them with a meaningful experience about the process and methods that engineers use to solve problems. In this course, students are required to complete a design project that meets criteria and culminates in testing of the design and analysis of the results. The second course shows how engineers use principles from the physical sciences to solve problems and design systems. In this course, students design a system or process involving computer programming and physical assembly of components. The system may be robotic, hydraulic, pneumatic, or mechanical in nature. Students also conduct standard tests and measurements, analyze and interpret experiments, and apply experimental results for improvement of their designs.

During the summer of 2012, students in the “The Engineering Process” course developed their spatial visualization skills using worksheets and sketching methods, studied the engineering design process, learned the basics of 3D modeling using CAD software, and were challenged to develop a design for a Lego Block and/or K’Nex separator for a child with limited physical dexterity. (A prior grant-funded course employed simulation software to introduce students to 2D graphics before learning the 3D CAD software.) The 3D model of the K’Nex separator, (see Figure 2), and the Lego Block Separator (see Figure 3), were modeled by students in the course and analyzed for functionality by performing motion simulation and Finite Element Analysis (FEA) to illustrate the iterative design process. 3D Printing capabilities were not available to the students in the course, but a tour of the Michigan Tech Open Sustainability Technology (MOST) lab provided students a glimpse of the RepRap 3D Printers being used for research.

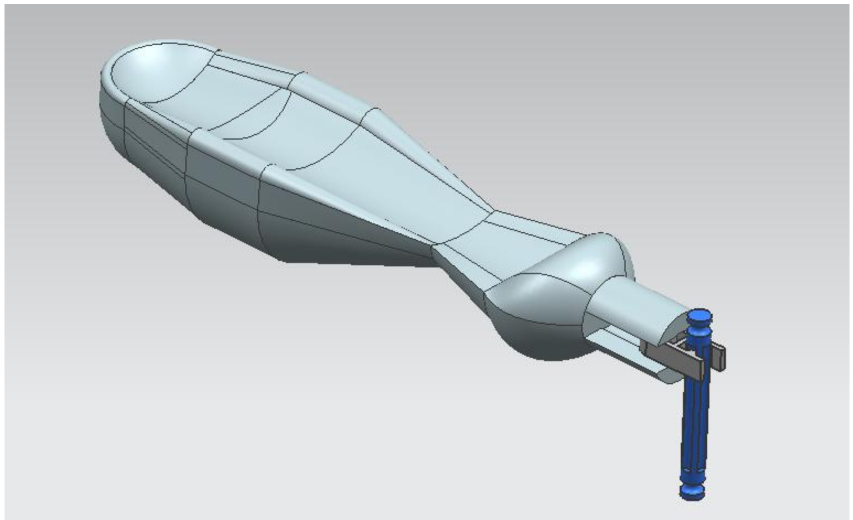

Figure 2. Student NX software 3D CAD Model – K'Nex Separator

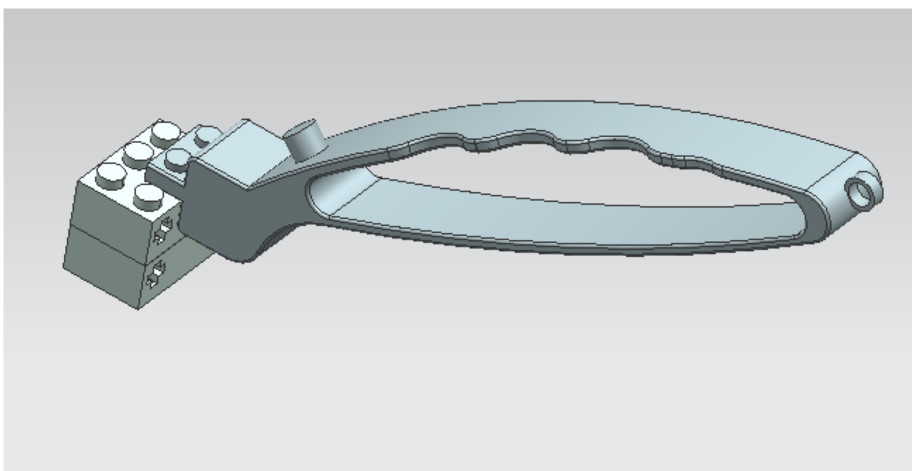

Figure 3. Student NX software 3D CAD Model – Lego Separator

Comments provided on a formative feedback survey after the course indicated that developing spatial visualization skills and utilizing 3D CAD software provided the participants a better understanding of the engineering process. Further long-term study is necessary to assess if this type of teacher professional development affects students' decisions to enter STEM fields after high school graduation.

In June of 2013 the "Engineering Applications in the Physical Sciences" course was offered. During the first half of the course, students built and tested wind turbine blade designs using a kit that required them to solder a circuit board to convert AC to DC and double the voltage (see Figure 4). A box was required to protect the electronics from the environment and instead of purchasing commercial version at a cost of $5-$10 USD, a customized potting box model was developed using CAD software and printed on the MOST Prusa Mendel RepRap to illustrate the versatility of 3D printers (see Figure 5).

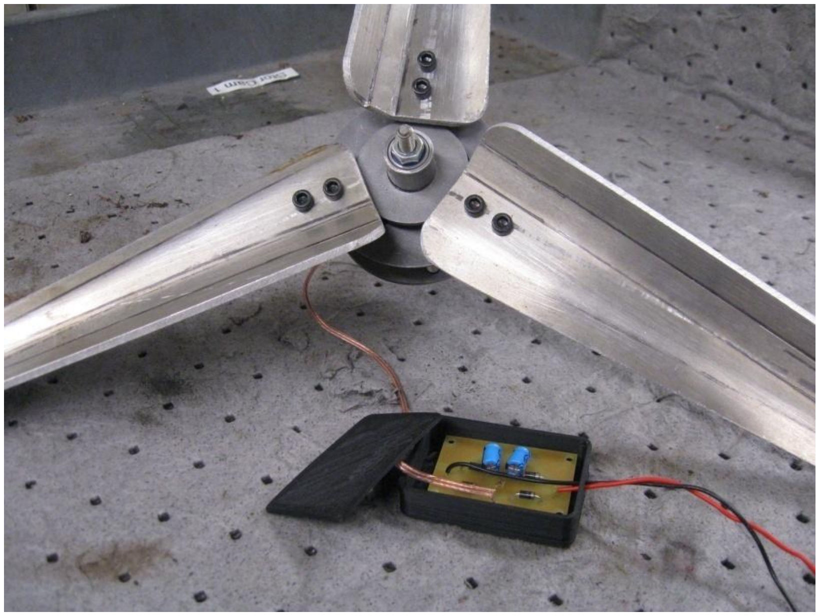

Figure 4. 3D Printed Circuit Board Potting Box

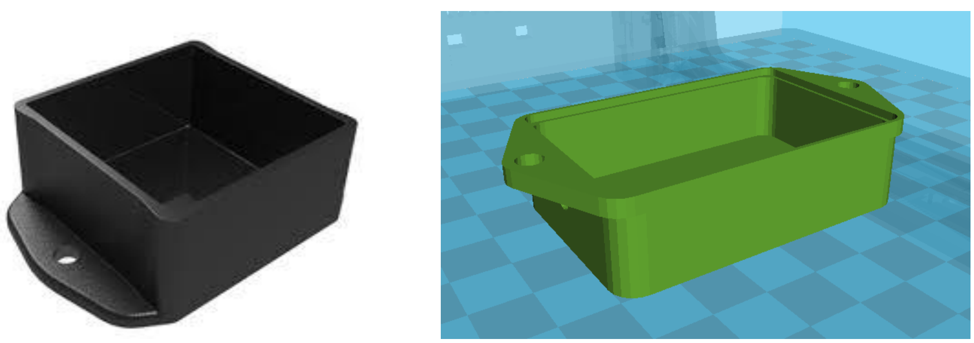

Figure 5. Circuit Board Potting Box Designs (without Lid)

In July of 2013 “The Engineering Process” course was delivered wherein students had an activity requiring the solution to a design problem for a customized flashlight bracket permitting attachment to various objects like a RepRap 3D Printer or bicycle handlebars. The project again allowed student groups to utilize the design, build, and test iterative process. RepRap 3D Printers were used in the class to produce several iterations for testing and improving their designs. The 3D Printer flashlight bracket design and the bicycle handlebar designs are in Figures 6 and 7. Students were asked to provide anonymous course feedback at the completion of the course using a survey. The students were asked to rate the flashlight clip engineering process project using a scale of 1-5, poor to excellent, and to discuss their thoughts about the project. From the

18 surveys returned the project was rated 4.5 on average with several comments pertaining to the value of creating the 3D Print of their design. Comments by the participants included:

> *"This was my favorite project, (and) creating a prototype was inspiring.", "Loved that we were able to actually print out our product.", and "It took us extensively through the design process and let us create a final product."*

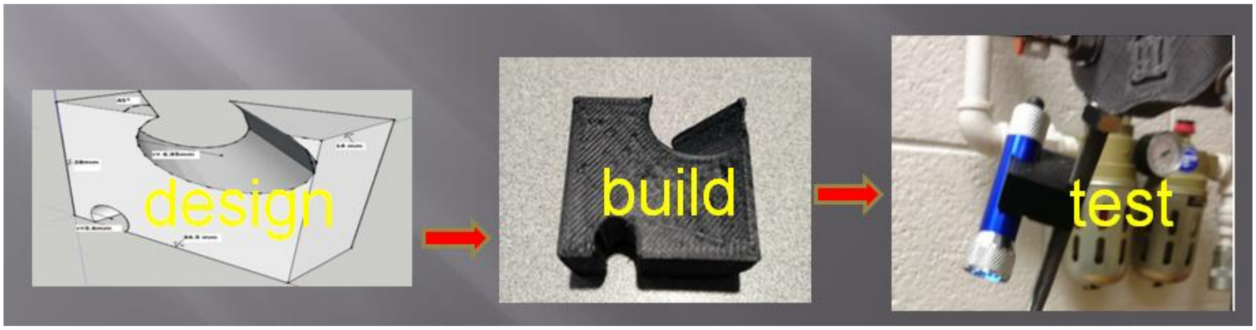

Figure 6. Flashlight Bracket for 3D Printer

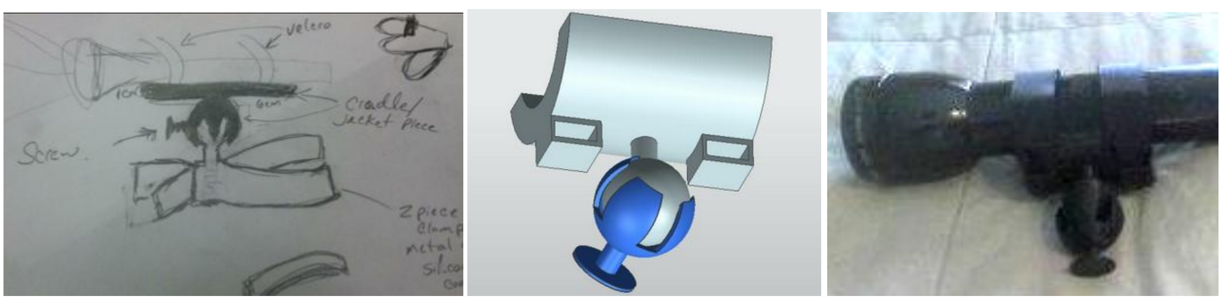

Figure 7. Flashlight Bracket for Bicycle Handlebar

During the two week course two students who are practicing high school biology teachers attended a two day workshop to build a MOST Prusa Mendel 3D Printer. They were particularly interested in applying the 3D printer to fabricate high-quality scientific equipment for their own classrooms, a method which has proven successful at the university level to radically reduce lab hardware costs for research.[17, 18] The participants accomplished the building and commissioning of the 3D printer to bring back to their high school biology class. They printed a mini centrifuge [19] and other apparatus for use in their classes (see Figure 8).

In addition, the opportunity exists for high school courses addressing the engineering standards to design and print scientific equipment for other courses. For example, an open source optics library has been developed that can be used to print a physics optics lab for $500, replacing about $15,000 of commercial equipment. [20]

Figure 8. Biology Teachers 3D Printer Build and Mini Centrifuge

Innovative Additive Manufacturing (IAM) workshop

In order to prove the viability of having high school teachers build and use 3D printers, a 3-½ day workshop was held during the summer of 2013. The “Innovative Additive Manufacturing” (IAM) workshop was the first of its kind and was funded by the Square One Education Network and MOST. Teachers applied to attend the workshop as teams of two from the same school or school district. Twelve teams were selected to attend the workshop where each built and commissioned a MOST Prusa Mendal RepRap 3D printer to take back to their school. The workshop used a self-paced program with four experienced facilitators available to help the 24 participants as they worked through a wiki-based, fully illustrated build process. In addition to building the printers, teachers were introduced to a completely free and open-source software tool chain (3D modeling, tool path generation, printer interface) used to design and print models.

Feedback from an online post-workshop survey was resoundingly positive, with participants expressing an empowering “can-do” attitude after building such a complex machine from scratch. They felt less fettered by the frequently dis-empowering “black box” approach typical of commercial technology and were more confident that they could fix the printer themselves. One survey respondent commented:

> *“This conference was an amazing revitalization on my own excitement for teaching and working with kids. I couldn't have taken more away in 4 days than I did and I haven't been this excited about getting back to school in decades!!!”*

The workshop also served to start a virtual community to support K-12 educational 3D printing. As part of this community many of the workshop participants have shared their triumphs and tribulations to help one-another in this new endeavor. Several teachers have shared their student’s work in solving engineering design problems using 3D CAD and 3D printing. For example, Figure 9 below shows a student-developed design for a bilge pump motor mount and propeller guard for use as a thruster on an underwater remote operated vehicle (ROV).

Figure 9. High School Student ROV Project Design

This design project, and similar projects by other teachers, are excellent examples of how this affordable technology can integrate the full spirit of the NGSS to ALL K-12 students, not just those who are in industrial technology type classes.

Delta Style 3D Printers

As the RepRap is an open source technology following a rapid technological evolution cycle [21], educators who have built a RepRap can use it to print parts for upgrades and contribute to the evolution of the design. Recently, several RepRap 3D printers have begun to appear using "delta robot" designs similar to those used for industrial pick-and-place applications. Delta RepRap 3D printers have a stationary print bed and an extruder that moves in all 3 axes which is different from the Mendel design which uses a Cartesian motion system with the extruder moving in the X and Z directions and print bed translating in the Y direction. The advantage of the Mendel design is that it uses more intuitive kinematics resembling how most machining centers operate, making it a good introduction to CNC machining. The Mendel design is also easier for K-12 students (and teachers) to conceptualize being that the motions are based on the Cartesian coordinate system used in their math courses. The Delta 3D Printer, although operationally less intuitive, is a very attractive alternative because it is simpler to assemble, requires fewer parts and requires less time to construct.

While the MOST Prusa Mendel RepRap costs about $550 and takes approximately 24 hours to build, the MOST Delta RepRap, as shown in Figure 10, costs about $400 and can be built in approximately eight hours once the full bill-of-materials has been collected. The value of high school students becoming active participants in the ongoing evolution of the RepRap printers' design can be more valuable than simply incorporating 3D printing into the classroom alone. Having access to a machine that they can take apart, fix, upgrade and try design experiments on provides a much richer learning environment than "press print" experiences with proprietary desktop 3D printers, which are normally sold at roughly 400% of the cost of a RepRap and frequently cannot be user-repaired. For example, the frame structure of the Delta design is made with fairly simple parts of metal or wood which means that these parts can actually be made by students in any school with access to a basic wood or metal shop. So with the capacity for students to design and create their own customized parts for these machines, the educational value and “student buy-in” is increased even further. (see Figure 10).

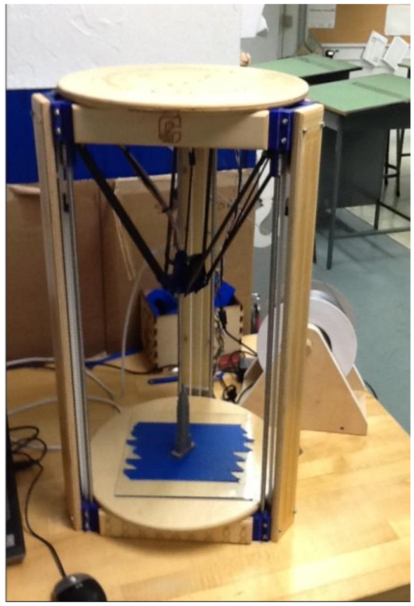

Figure 10. Customized MOST Delta RepRap

College STEM Course 3D Printing

High school science courses are utilizing 3D Printers to introduce students to STEM fields of study, but college and university courses are intended to prepare students for successful STEM related careers. In the MET curriculum at Michigan Tech there is a course called “Product Design and Development” that relates issues such as design for manufacturing, prototyping, industrial design, and customer needs. Since 3D Printing has become accessible using the RepRap printers, a lecture on 3D Printers now includes a live demonstration. The instructor simply rolls a cart with the 3D Printer and laptop into the classroom and leads the students through the steps from start to finish to create a plastic part from a CAD model. Students then follow-up the lecture with a lab activity, creating a CAD model that will integrate with an electronic communication device: Individualized cellular phone cases, speaker mechanisms, or charging docks are modeled, 3D printed, checked for fits and tolerances as well as function.

Conclusions

There are several desktop 3D printers available on the market today to implement design-build-test projects where students experience real-world application of the iterative engineering problem solving process. The affordability of the open source RepRap do-it-yourself design lends itself to direct manipulation of the 3D Printers because no warranties are being voided as high school and/or university students “tinker” with the mechanics of the 3-D printer and enjoy near-immediate gratification from experiencing the engineering process first hand. Students from high school to higher education who are engaged in hands-on design-build-test scenarios will attain a valuable skill set and be more likely to pursue STEM careers. These skills will also be useful for developing designs for capstone projects which are common in higher education and becoming popular in high schools.

Recommendations

Integrating RepRap 3D printers into curricula may be a perfect way to deliver K-12 science standards and university STEM program goals. If interested in implementing a 3D printer of any type, it is recommended that one consider aspects other than the overall cost. Some other factors that play a role in the 3D printer decision are; the printed part quality/accuracy, types of material options, plastic material cost, printing time, support material capabilities, and level of 3D printer adjustments and general maintenance required. Some of these 3D printer qualities are compromised with low cost alternatives like the RepRap 3D printer when compared to the production models.

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