PRODUCT FOCUSED FREEFORM FABRICATION EDUCATION

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Abstract

Presented in this paper is our experience of teaching freeform fabrication to students at the Missouri University of Science and Technology, and to high school students and teachers. The emphasis of the curriculum is exposing students to rapid product development technologies with the goal of creating awareness to emerging career opportunities in CAD/CAM. Starting from solid modeling, principles of freeform fabrication, to applications of rapid prototyping and manufacturing in industry sponsored product development projects, students can learn in-depth freeform fabrication technologies. Interactive course content with hands-on experience for product development is the key towards the success of the program.

Introduction

A product-oriented freeform fabrication curriculum has been implemented at the Missouri University of Science and Technology [1]. We have integrated the freeform fabrication related courses into a product realization curriculum to reinforce and sharpen critical competencies of students. This curriculum provides students with the experience of integrating engineering and business skills toward rapid and distributed product realization. This curriculum also provides students with the experience of integrating the technical knowledge they have learned from other courses. The course sequence includes a product modeling course, a rapid prototyping course, and an integrated product development course. The development effort for these courses is summarized in this paper, as well as a brief overview of several undergraduate level product design courses.

Product Modeling Course

The objective of this course, “ME 363: Principles and Practice of Computer Aided Design,” is to provide the students with some in-depth knowledge of the fundamental principles and underlying theories of computer-aided design and engineering and to provide them with the experience of working with a commercial CAD/CAM package. The emphasis of the course content is on geometric modeling. The topics of coverage include: 1) Introduction (engineering design process, CAD/CAM system concept, CAD/CAM hardware and software); 2) Representation of Curves (analytic curves, synthetic curves, manipulation of curves); 3) Representation of Surfaces (analytic surfaces, synthetic surfaces, manipulation of surfaces); 4) Representation of Solids (constructed solid geometry, boundary representation, other solid modeling methods); 5) CAD/CAM Data Exchange (data types, exchange methods); 6) Graphic rendering (coordinate transformations, projections, wireframe drawings, shading & smoothing); 7) Finite Element Analysis (element & node types, deriving and solving system equations). The NX/Unigraphics software package is used by the students to perform design of components and products. This also helps them grasp the fundamental knowledge given in the lectures. The lab exercises cover features creation, sketching, solid modeling, freeform surface modeling, geometric editing, assembly modeling, automated drafting, and finite element analysis. The connection between CAD and CAM is made through demonstration of NC machining and rapid prototyping of physical parts from CAD models. This course is internet accessible to accommodate distance-learning students.

Rapid Prototyping Course

The aim of this course, "ME 308: Rapid Product Design and Optimization," is to discuss the engineering procedure and the practice of applying rapid prototyping technologies to quickly deliver new products with lower cost and higher quality. Students not only learn about rapid prototyping technologies, but also gain a good understanding of using physical prototyping for product design and development with modern technologies and tools. The basics of the rapid prototyping procedure are introduced. They include: 1) Constructing a CAD model, 2) Converting a CAD model into an STL format, 3) Checking and fixing the STL file, 4) Slicing the STL file to form layers, 5) Producing physical RP models, 6) Removing support structures, and 7) Post-processing RP parts. Various RP processes, such as liquid based processes (SLA, SGC (Solid Ground Curing) [2, 3], Rapid Freeze Prototyping [4-6], etc.), solid based processes (FDM [3], LOM (Laminated Object Manufacturing) [3, 7], UC (ultrasonic consolidation) [3, 8], etc.), and powder based processes (SLS, LENS [3, 9], LAMP [3, 10]) are also introduced. The application of rapid prototyping and other technologies to product realization is also introduced. Students have access to various RP processes, such as FDM, SLS, RFP, and LAMP, for part fabrication or for research. At the end of this course, a concept prototype of a sponsored project is implemented. The sponsors include industry, university research labs, and some private individuals/parties.

Integrated Product Development Course

A project-based course, "ME 358: Integrated Product Development," is also offered in the curriculum. The focus of this course is to develop an engineering prototype. The semester projects are the focus of this course, and could be a continuation of the sponsored project from the previous RP course. This course enables the students to learn the following subjects: 1) acquisition of customer's requirements, 2) problem formulation, 3) prototype cost estimation, 4) prototype conceptual design, 5) product/prototype representations, 6) product concept prototyping, 7) make or buy decision, 8) manufacturing process capabilities, 9) prototyping process identification, 10) assembly, and 11) prototype assessment.

In this course, interdisciplinary teams with students from various disciplines work together to design, manufacture, and assemble real-life products. Students in the Missouri S&T M.S. degree program actively participate in the project as part of their practice-oriented credit requirement. The project courses take advantage of the manufacturing options being offered by both the Mechanical Engineering and Engineering Management departments. It is intended to simulate the modern industrial product development and manufacturing process in which engineers from various disciplines work together, and each team member contributes his/her expertise to accomplish the project. Students in Mechanical Engineering have a solid background in product configuration/definition/analysis, process development, and some rapid prototyping and manufacturing processes; students in Engineering Management have good knowledge in marketing/cost analysis, quality engineering, and project management; students in Manufacturing Engineering are more familiar with prototyping and manufacturing processes, and hands-on fabrication experience. They work in teams to perform concurrent product design and prototyping.

Their customer is the sponsoring company that is interested in prototyping a product, or in testing a new prototyping process. Student teams make presentations each week to report their project progress. This way they can learn from each other at various product prototyping stages. We have found that this also provides great motivation for each team to keep good pace with the other teams.

Basic Product Design Courses

There are several undergraduate level product design courses on campus. Most of these courses use RP processes, such as Stratasys FDM and Dimension machines, as a part of the design prototyping tool in the semester projects. The freshman design course "IDE 20: Engineering Design with Computer Applications" is an introduction to software tools (computer-aided design and drafting, computer mathematics, word processing, spread sheets) with application to engineering practice. It also includes principles of engineering design. A semester long group design project is an integral part of the course. "ME 161: Introduction to Design" introduces the process of design with emphasis on creativity and design visualization. Students are taught to produce elementary, workable mechanical designs involving several design projects. This course is designed to teach students basic design methodology. Included are tools to facilitate problem clarification, develop product performance specifications, generate feasible solutions concepts, and select a best concept. In addition, there is an emphasis on solid modeling as it complements graphical communication and leads to workable mechanical drawings. "ME 261: Engineering Design" is focused on real-life design projects emphasizing problem definition, conceptualization, modeling, approximation techniques and optimization. Teamwork, communication, leadership and group discussions are encouraged. Student group and professional expert presentations bring awareness to diverse design issues and methodology, and professional engineering practice.

Prototyping Facilities

Since prototyping and manufacturing facilities are very capital intensive and require constant maintenance, it is a major challenge to maintain all facilities for students to use. Many of the experiences of the prototyping realization process concurrently gained by students are severely limited by the types of prototyping processes available at their universities. Also, it is unrealistic to expect that every institution will be equipped to handle a broad range of "real-life" products used for product realization projects. We have used the existing campus prototyping resources and those available from industries to provide distributed prototyping experiences for students. Figures 1-5 show some of the rapid prototyping facilities on campus. One unique feature of the curriculum is the distributed product realization that ties together the prototype realization process and supply chain management.

Figure 1. SLS 2000 Machine.

Figure 2. Stratasys Dimension Machine.

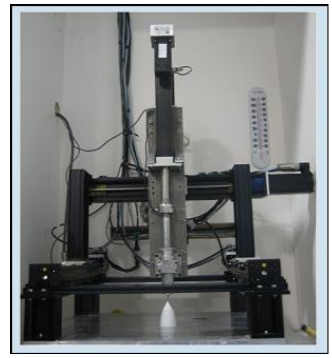

Figure 3. Freeze-form Extrusion Fabrication (FEF) Machine.

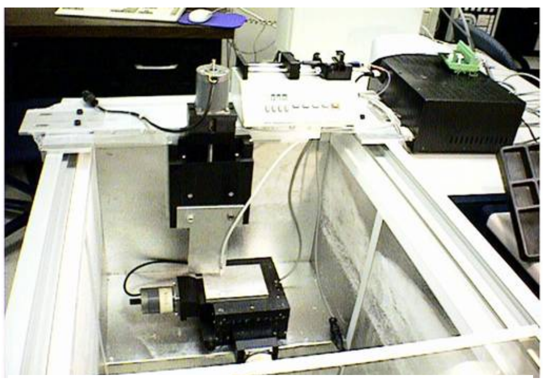

Figure 4. Rapid Freeze Prototyping (RFP) Machine [4-5].

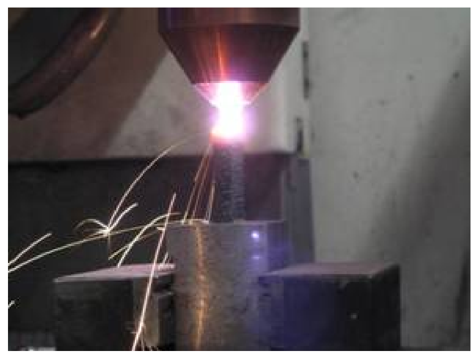

Figure 5. Laser Aided Manufacturing Processes (LAMP) Lab [10].

Students have access to the internet, handbooks, and catalogs to procure parts. Furthermore, students also have access to a selected list of vendors/suppliers (with varied degrees of manufacturing process capability) who would supply quotes based on the design drawings supplied by the student team. Based on product complexity, the student team is provided with the approximate percentage of parts and part types that can be prototyped in-house at the university, procure "off-the-shelf" components from catalog vendors, or request bids for some of their component drawings with vendors. Through this scenario, we will be able to provide students with the experience and "know-how" of the tactical advice on developing effective logistics of operations and unique insight into the operating environment for sourcing and procurement. For example, students can produce a product by making parts in-house, working with a vendor to produce a plastic or composite component, or matching and integrating with an ordered motor through the catalog. The integration, management, and communication involved in the process are a meaningful experience for all the students participating in the project.

Partnerships with Industries

The partnership with industry is a critical step to the success of the curriculum. In the past few years, many companies have participated in the project course by sponsoring the capstone projects. They include:

- WOOD PRO, Cabool, MO
- EYES OF THE WORLD, Rolla, MO
- WATLOW INDUSTRIES, St. Louis, MO
- META STABLE, St. Louis, MO
- DESIGN OPTIMIZATION TECHNOLOGIES, St. Louis, MO
- PRIER PRODUCTS Grandview, MO
- MISSOURI ENTERPRISE, Rolla, MO
- FORD MOTOR COMPANY, Detroit, MI
- GENERAL MOTORS, Detroit, MI
- THE BOEING COMPANY, St. Louis, MO
- PRODUCT INNOVATION AND ENGINEERING, LLC, Rolla, MO
- SPARTAN LIGHT METAL PRODUCTS, Inc, Sparta, IL
- RPM AND ASSOCIATES, Rapid City, SD
- INTELLIGENT SYSTEMS CENTER, MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY, Rolla, MO
- NATIONAL SCIENCE FOUNDATION
- AIR FORCE RESEARCH LABORATORY, Wright-Patterson, OH
- Several individual inventors

These companies also invested their engineering time and other resources. Students were given real-life projects based on manufacturing processes and were required to analyze unit steps and suggest possible innovations. Many industries have instituted worker incentive programs that seek suggestions for product and process improvement. This concept was introduced in the classroom to train young minds to 'think differently' and plant the seeds for them to become future process innovators.

Project Examples

These classes have been offered for the past seven years. We have found that the students are very interested in working on emerging products that are current and intriguing. Two products are briefly summarized here, including a laser beam steerer and an EDM machine.

Laser Beam Steerer Example

The objective of this project is to design and develop a laser beam steerer used for mounting on the exit aperture of a commercial laser used in laser machining or laser modeling operations. This device will serve as a platform for all future automated laser mounting devices. Our device will be primarily targeted at the laser operating market, with the secondary targets being for spectrometers and projectors.

After assessing the customer needs, the team developed a House of Quality scoring matrix. This is an extremely valuable tool to get a first-hand view of how to prioritize prototype objectives. This concept was benchmarked against other beam steerers in the market to get an idea as to how it compares with others.

The team used brainstorming techniques to come up with several different concepts for the beam steering device. A concept-scoring matrix was then put together to discover which of the ideas was the best. The three ideas that the team came up with were placed in a matrix, which weighted the various selection criteria. The different concepts are represented using virtual models as shown in Figures 6-8.

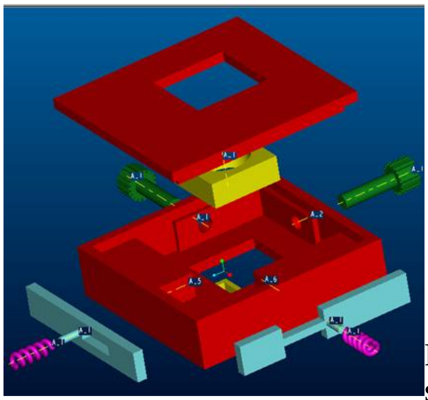
Figure 6. Concept 1: Rail with Bungee (Original design) solid model.

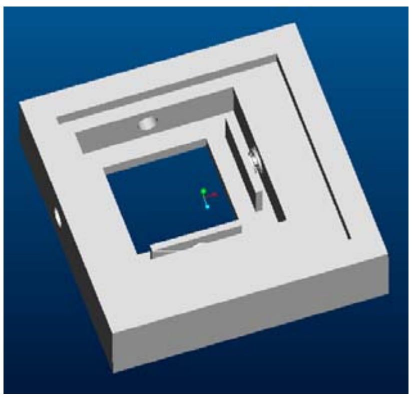
Figure 7. Concept 2: Simple rails solid model.

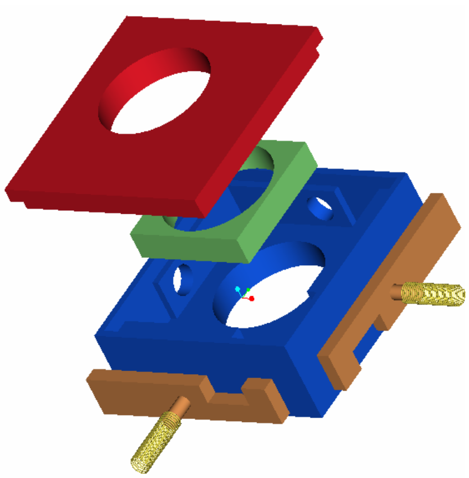
Figure 8. Concept 3. Spring rails solid model.

After the needs and concepts were defined, using a concept selection matrix, the rails with the spring idea were selected as the final concept. The team then came up with some physical prototypes to evaluate the concepts as shown in Figure 9.

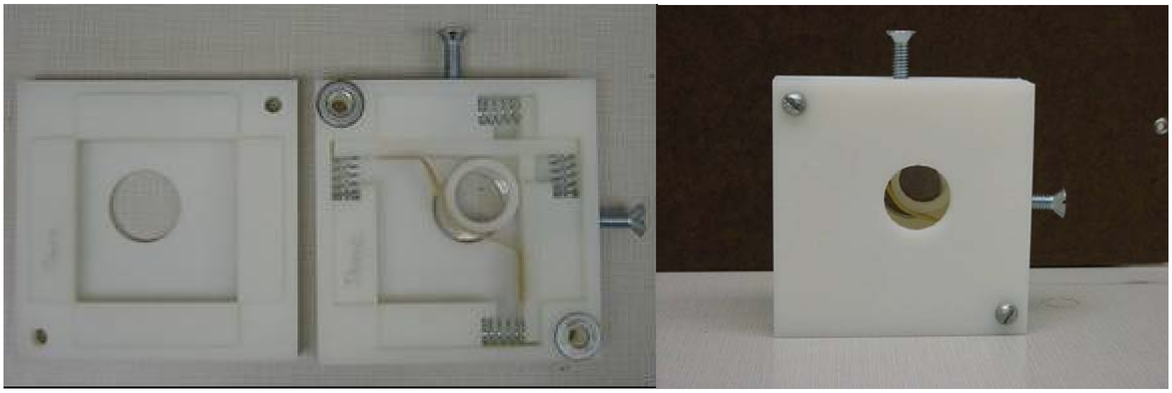

Figure 9. Alpha prototype design with major parts using rapid prototyped components.

After some testing of the prototype, some minor redesigns were made. The bill of materials was generated for the detailed concept. Solid models of all the parts were generated using a solid modeler, and the different parts were assembled to check for any interference. Tolerance analysis was conducted to ensure proper functioning of the final assembly. Cost analysis was made and time for manufacturing was found.

The final manufacturing of the parts as shown in Figure 10 was fabricated on Dynamite, a CNC milling machine at the Integrated System Facility (ISF). Finishing operations were completed in the ME department's machine shop.

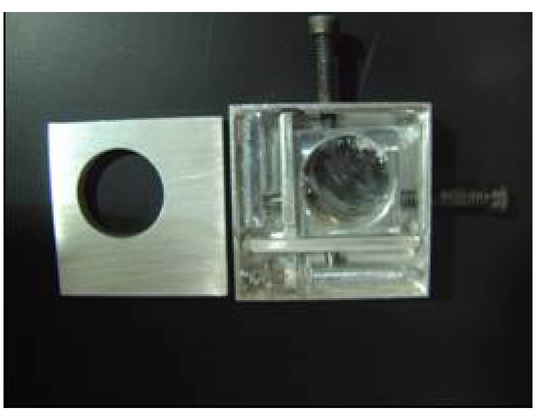

Figure 10. Final manufacturing of the design.

The final prototype met all the requirements of the customer. The size of the laser beam steerer was reduced to a 2"x2" dimension. The product was manufactured in aluminum.

<u>Wire-EDM Machine Example</u>

The objective of this project was to design and construct a desk top sized Wire EDM which can cut simple 2D figures on electrical conductive materials, such as titanium alloys and tool steels. The prototype cost should be controlled within $1,000. The machine includes four systems: wire supply system, X-Y table control system, tank and electrical circuits.

The virtual prototype for Wire-EDM was built using CAD modeling as shown in Figure 11. Figure 12 shows the sample sub-assembly and components. The purpose for building the virtual prototype includes the following: 1) Check the design plan. For example, when the prototype was built, it was found that there were some errors in the original design plan, thus the parts could not be assembled properly with the standard components; 2) Make all the parts easy to machine. With the 3D model, it is easy to generate 2D and 3D drawings and communicate with the machine shop, and consequently saves time and energy; and 3) Makes the assembly process easy. Completing the assembly in a virtual environment makes the operators familiar with the process.

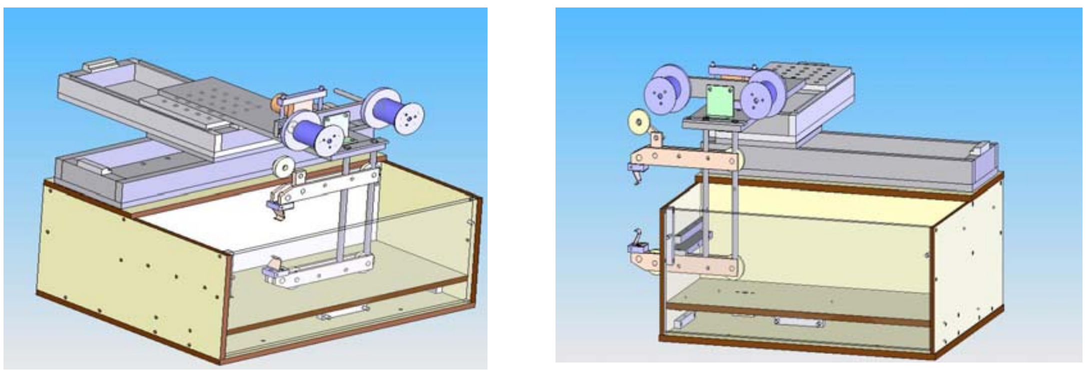

Figure 11. The virtual prototype of the Wire-EDM.

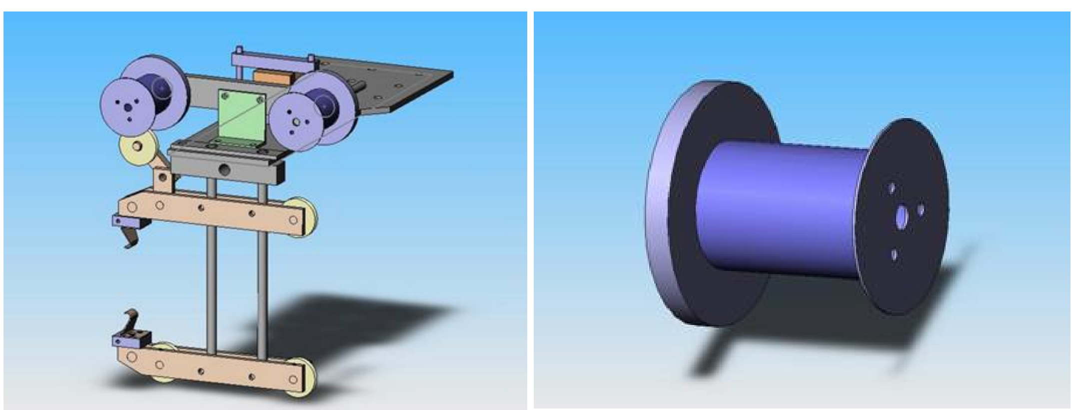

Figure 12. Sub-assembly examples.

Several manufacturing processes were identified to machine parts for this Wire-EDM: 1) Cutting. Cut the raw material including aluminum, steel and Trespa to proper size to be machined; 2) Milling. A mill was used to machine the block parts; 3) Turning and boring. A lathe was used to machine the pulleys, etc.; 4) Drilling and broaching. Drill and broach holes were used to assemble the parts together; and 5) Rapid prototyping. FDM (Fused Deposition Modeling) was used for physical prototyping and for actual fabrication of some parts as shown in Figure 13.

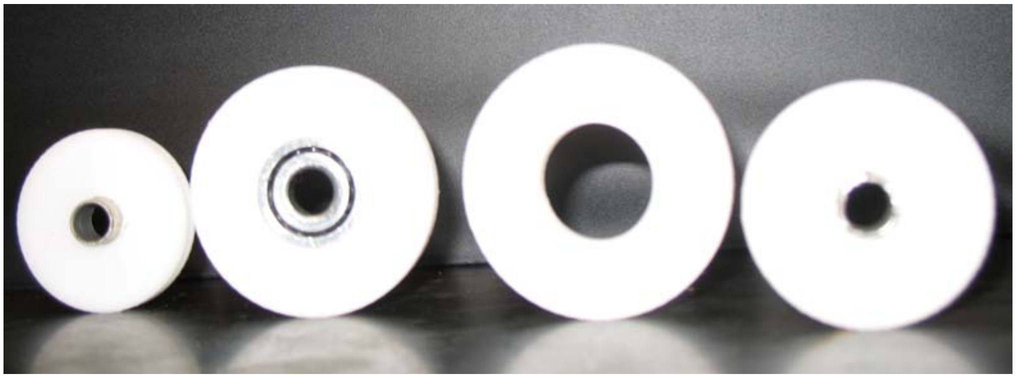

Figure 13. Rapid prototyping of components for Wire-EDM.

Figure 14. Realization of the wire-EDM machine: system oval (left) and cutting a titanium sample (right).

Figure 14 shows the complete prototype of the wire-EDM machine. It can cut both titanium and tool steel. Although the cutting speed can still be improved, this project was a success and the customer is satisfied. The total project cost was $884.

Outreach to High School Students and Teachers

The rapid prototyping curriculum was also used to educate high school teachers and students. Many youths and young adults have little knowledge of engineering and manufacturing career options. Parents, teachers, and educators lack the exposure to understand the highly technical manufacturing world. Early education is a key element to engineering and manufacturing career awareness. Rapid Prototyping is an emerging technology in manufacturing. It is a fast and effective way to develop the prototype parts from their CAD models directly. These parts serve the purpose of design evaluation in the early stages of the product life cycle.

A rapid prototyping session was held in the 2004-5 NSF sponsored "Discover Manufacturing Workshops," which introduced new technologies and concepts to the workshop attendees. This workshop was a collaborative effort between the Missouri University of Science and Technology and the St. Louis Community College at Florissant Valley. Its purpose was to expose high school students and teachers to manufacturing technologies in the hope of directing and impacting their career choices. The workshop was a week long program covering most of the areas in the manufacturing sector. The schedule for the workshop is shown in Table 1. The week started with an introduction to solid modeling. NX/Unigraphics was used as the CAD tool to give the attendees hands-on experience in solid modeling. The next day we introduced rapid prototyping which was a new concept to most of them. They had hands-on experience on two machines, namely FDM and the Thermaljet. Later in the week they were exposed to CNC machining, lean manufacturing and quality control.

Table 1 – Workshop Schedule

Mon.	Activities
9 am	Introductions and orientation
10 am	Manufacturing overview
10:40	Solid Modeling
11.30	Lunch Break
12:15	Solid Modeling
2:15	Solid Modeling
3:45	Wrap up day
4pm	Dismiss

Tue.	Activities
9 am	Introductions
9:15	Rapid Prototyping Introduction
10:15	Rapid Prototyping Lab
11.30	Lunch Break
12:15	Rapid Prototyping Applications
2:15	Rapid Prototyping Post processing
3:45	Wrap up day
4pm	Dismiss

Wed.	Activities
9 am	Introductions
9:15	CNC Machine Trainers
11.30	Lunch Break
12:15	Manufacturing Industry Tour
3:45	Wrap up day
4pm	Dismiss

Thur.	Activities
9 am	Introductions
9:15	Lean Manufacturing
10:30	Lean Manufacturing
11.30	Lunch Break
12:15	Lean Manufacturing
2:15	Lean Manufacturing
3:45	Wrap up day
4pm	Dismiss

Fri.	Activities
9 am	Introductions
9:15	Quality Control
10:30	Quality Control
11.30	Lunch Break
12:15	Plastic Processes
2:30	Guest Speaker
3:45	Wrap up day
4pm	Dismiss

The feedback we received from the workshop attendees was very encouraging; teachers were able to relate mathematics and computer application with design, drafting and finally to produce the prototypes. They were in a better position to guide students concerning career opportunities in manufacturing. Based on the feedback, the workshop was very helpful in assisting the students with selecting a career.

Conclusions

The freeform fabrication curriculum at the Missouri University of Science and Technology has been summarized in this paper. The virtual and physical modeling capabilities enable students to develop products with faster speed and higher quality. The current focus has been on the emerging products as the students find these projects intriguing. The sponsorships are critical as they allow students to purchase critical components. However, some of the facilities require excessive training before they can operate the machinery. Therefore, careful coordination and planning of team members with the appropriate background are important when forming the team.

The feedback and results are very encouraging. Based on our experience so far, we have found that the major challenges encountered were project timing and facilities. The students greatly benefited from the weekly project presentations given by each group. This not only forced them to keep pace with the other groups in the project schedule, they also learned from each other on how to proceed through each of the steps. According to the students' feedback, the fact that they could simultaneously observe the other projects including how the other groups defined their projects, formulated the problem, designed the product, ordered the off-the-shelf components, fabricated the parts, and put them together, was a great learning process.

Acknowledgements

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