Reverse Engineering and Rapid Prototyping: A Senior Level Technical Elective for Mechanical Engineering Technology Students and Much More.

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Abstract

Students in the Mechanical Engineering Technology (MET) program at Penn State Erie, the Behrend College are highly versed in application oriented computer techniques for problem solving. Nine years ago, a senior level technical elective was developed that would allow students with an interest in CAD modeling and design extending beyond the nine credits of required CAD classes to further their knowledge of the latest technology. This course would also introduce students to aesthetic and ergonomic design issues, which, while touched upon in traditional design courses, have never been a major factor in the overall design process. Over time this course has evolved to one that also covers advanced surface modeling CAD strategies for geometry creation, both additive and subtractive methods for rapid prototyping and different methods of reverse engineering existing products. In addition, the acquisition of this technology and equipment has come to benefit both students in other courses and departments within the College. It has also become a resource for faculty doing research and local industry as well. This paper will describe the scope and layout of this class, student projects, and the equipment used, associated costs of running a laboratory and lessons learned as well as the impact on other faculty, departments and local industry.

Course Overview

METBD 410 (Rapid Prototyping, a technical elective) has the following Goals/Objectives:

1. Understand the advantages and disadvantages of different additive processes currently on the market.
2. Reverse engineer a product by digitizing geometry, importing the data into Pro/ENGINEER and creating a solid model from surfaces.
3. Build the model (Objective 2) on the Z-402 3-D printer and re-digitize the prototype using a non-contact scanner to verify the geometry against the CAD model. Iterate through Objective 2 and 3 as needed.
4. Create CNC tool paths for three axis milling operations including volume, local, conventional, contour and trajectory, using Pro/MFG on the CAD model.
5. Check tool paths for accuracy using Pro/NC-CHECK.
6. Post process all tool paths and execute them on a three axis CNC router.

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Prerequisites for this class are nine credits of CAD. These are all required courses in the Mechanical Engineering Technology program and consist of Introduction to Graphics and Solids Modeling (3 credits), Applied Solids Modeling (3 credits), both freshmen level courses and Computer-Aided Design (3 credits), a junior level class..

Course discussion in order of amount of student time spent on each objective:

In order to accomplish the second objective (Create a solid model from digitized geometry) require a pretty though knowledge of surface modeling. Starting from discrete data points, students must create curves through these points, use these curves to create surfaces and then be able to merge the surfaces together to form water tight geometry to finally produce the solid. To do this, a combination of traditional surfacing techniques as well as the use of the Interactive Surface Design Extension module (ISDX) in Pro/ENGINEER is taught.

Initial teaching methods:

Varying methods of instructional methods have been used to teach surfacing methods. A traditional lecture discussing and demonstrating the methods followed by a laboratory assignment has been most used. What has changed has been the nature of the lab assignments themselves. Early on assignments could not be aligned to the semester project as students chose their own projects. The result was that a majority of the course grade was based on weekly lab assignments related to surface modeling. These topics might or might not be useful to the student when working on their project as they chose their project. This is explained under the Student Projects portion of this document.

Before we had a lab fully equipped and dedicated to Reverse Engineering and Rapid Prototyping, the course was primarily that of a higher end solids modeling class coupled with survey elements where different methods of additive and subtractive technology were presented. Surface modeling was introduced where the students would start with 3-D curves, produce surfaces from these curves, merge the surfaces and convert the surface geometry to solids. Lab work consisted of doing discreet surfacing assignments. At the time we had no additive equipment, and the only subtractive equipment we had access to was a 3-axis CNC mill which was shared with our machining technicians for the school. To practice applications using the subtractive process, the students would take a virtual model of small boat, encase it into a die block and produce upper and lower die halves of a compression mold. The students then generated the tool paths using Pro/Manufacturing within Pro/ENGINEER and then machined the molds. The students did all the machining work, from fixturing the raw stock, to setting the tool offsets, loading the files and running the tool paths. These molds were made from machineable wax and casting wax was melted and compressed in the molds to produce parts.

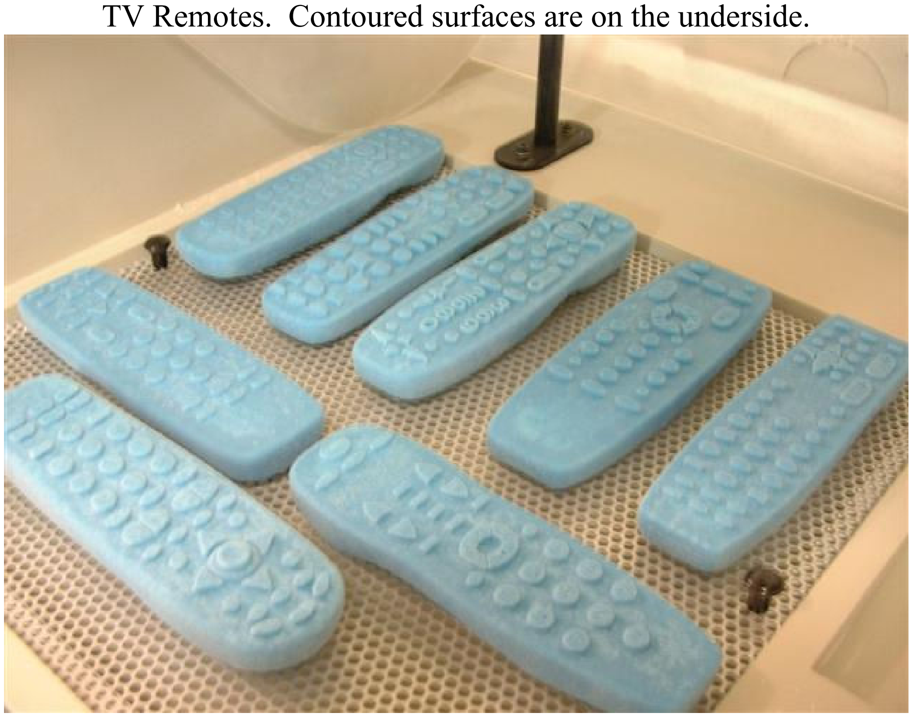
History of student projects relating to course goals:

Projects have varied from instructor assigned to student selected. Early attempts were made having students select their own project. The theory behind this concept was that students would establish ownership of their project and if they are working on something they are interested in are more inclined to spend the time required to produce a "perfect" product. Unfortunately, it is difficult to keep students from tackling projects that are far beyond their capabilities, which leads to frustration, or so simple that the student can't maintain an interest in the project. In some cases, students simply select a project because they need to have something (anything) to work on. It doesn't necessarily mean they have an interest in the product. Projects of this nature ranged from modeling a SR71 Blackbird aircraft which the student machined from cherry wood to modeling an lighter machined from foam insulation.

Instructor assigned projects have been more successful, depending upon how the assignment was structured. An early attempt was reverse engineering a model car. The instructor went to a toy store and selected pre-built model cars that were good candidates for the process. Attention was paid to the geometry of the model to make sure that it was not overly complex. Example: a Corvette is easier to model than an older model VW bug as the Corvette has a smoother overall shape. The bug has a lot of surfaces that meet at sharp edges such as the wheel wells and the body that make collecting the data somewhat difficult. Students could then take their pick of what car they wished to work on. These models are usually popular with students in a Mechanical Engineering Technology program. Unfortunately, even modeling simple car bodies become overly complex in a real hurry.

An effort was made to simplify the process even more. Remote controls for TV's and one piece cell phones have also used.

TV Remotes. Contoured surfaces are on the underside.



Students are taught that "Designs that look fine on screen often don't work in the real world". (1) In an industrial setting, one might model a product on the computer and then use a 3-D printer to produce a quick and dirty prototype before refining the concept. The engineer doing this task has a pretty good idea of how the part should look and function before beginning the process. Students, on the other hand, usually have no real background on a part that they are asked to model. This is not their fault as they have no real prior life experience in the background or history of the product. They also have not developed any sense of proportion or have a real understanding of how form and function might be related. It is impossible to learn these concepts in a short period of time. Printing initial concepts on the Z-402 3-D printer was chewing up too much time (instructor, student and printer). When students made modifications to the initial geometry, the changes were difficult to incorporate into CAD geometry and subsequent 3-D prints were usually not much better than the initial ones. The basic problem is as follows:

What comes first, the chicken or the egg?
Assume the following criteria must be met: A TV remote should fit comfortably in your hand. Question (Q); How do you know if it is a good fit? Answer (A); You have to have a physical model to hold. Q; Where does the prototype model come from? A; The model is produced on a 3-D printer. Q; What do you need to print the model? A; The 3-D printer requires a file in .stl format, produced from a 3-D solid (or surfacing) modeling program. Q; How do you define the shape of the CAD model? A; The shape is defined by curves which are used to produce the surfaces. Q; Where do the curves come from? A; The curves are defined by a shape that fits comfortably in your hand, and we are essentially back to where we started.

What we finally hit upon was having a student literally sculpt their initial concept out of modeling clay. This accomplished a number of things. It allows the student to view/manipulate their concept in 3-D without having to first produce a CAD model and then use the 3-D printer to review an initial concept. The instructor can quickly add/subtract or manipulate the clay to help the student at least get to a point where they have a good place to start. In this case, data will be taken off the clay model using the Microscribe 3-D digitizer and imported into the CAD system to begin the curve/surface generation process. Using this method, goal number two for the course can be accomplished in a minimal amount of time

Example of a recent student project. From right to left, purchased Nemo toy, clay model, Z-402 part, ½ model in foam created on CNC router ("mouth" is actually an operator error), ½ wooden model in MDF machined on CNC router.

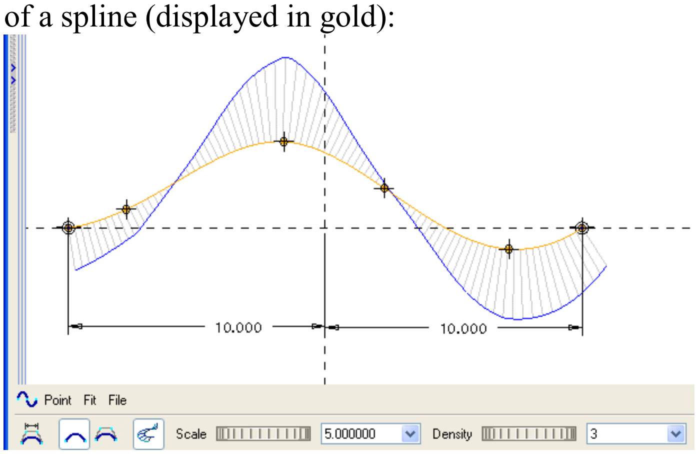
Concepts that students seem to find the most difficult:

When one captures (digitized) data from a physical model, there is noise in the data. Some points will not be exactly on the true surface and points will not be purely planer. In order to construct curves which represent cross sectional data on the surface, these curves must be both fair and at the same time accurately reflect the surface geometry. The Microscribe digitizer is only accurate to +/- .009, the physical model may or may not be perfect and the locations where the points are taken may not be planer.

Students must develop an "eye" for good curve data as well as a methodology for collecting enough geometry so the part can be effectively replicated. More data is not always better as too many cross sections will be difficult to fair and too few sections will cause critical geometry features to blend away to nothing. Since students have little to no experience in creating a family of smooth, fair curves, this is a challenge for most. The students are cautioned from day one that surface geometry is totally dependent upon the underlying curves, but until they have experienced it for themselves they seem to ignore the issue. It seems so easy to take some points, draw curves through them and then produce surfaces. Tangency conditions on curves and surfaces are highly stressed. Since most parts are symmetric about a centerline, care must be taken to make sure each curve is normal to the center line datum at the centerline and the end of the curves intersecting the horizontal parting surface (if only modeling one half of a part) or horizontal plane must also have appropriate end conditions such as a constant draft angle.

Pro/ENGINEER has tools that allow one to analyze geometry, but a lot of this is meaningless until the student has produced a really ugly surface model and then held it in their hand. Most students will digitize their project, start to create curve and surface geometry and realize that what they have and what they need is two different things. They will then return to the digitizer with a new methodology in order to get it right. This seems to be the norm, even though there have been prior assignments given where noisy data has to be faired by the students. Again, all of this is in support of class objective number two.

Tool inside of Sketch mode of Pro/ENGINEER to display curvature of a spline (displayed in gold):



One of the unwritten goals of the course is to bring the student to the point where they will not be so quick to say that Pro/ENGINEER (or any other CAD software) is not capable of producing such and such type geometry. Rather the student should be able to indicate that it is possible to model such geometry if in fact the geometry is required to accomplish the overall look and feel of a product as well as being manufactured through the use of surface and solid modeling techniques.

Up to this point, most of the discussion has been on surface modeling itself. Course objective number one (Understand the advantages and disadvantages of different additive processes currently on the market) also dovetails into this mix. Producing parts using additive technologies is critical to quickly generating prototype parts that are composed of highly blended and contoured surfaces. The additive industry (where machines start with "nothing" and produce parts using a layering technology) is slowly maturing, and major players such as 3D Systems, Stratasys and Z Corporation have firmly established niches, but the industry is still in a state of flux. The state of the overall economy has influenced this industry as the technology is relatively new and therefore expensive. Emerging technologies such plastic lamination machines being sold by Soliddimension Ltd. and others outside the U.S. are reviewed. It should be noted that a fair number of technologies will not be available in the U.S. due to patent restrictions. Technologies that are still being researched such as the Rapid Freeze Prototyping (2) that produces parts made of ice and is being developed at the University of Missouri-Rolla are also covered. Since the industry is changing with new companies, technologies and products being introduced (and being retired) so rapidly, it is necessary to review each item each and every year via the internet to make sure the information being presented is accurate and up to date.

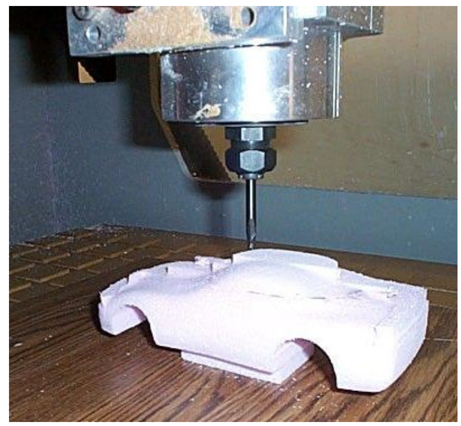
The final exam in the course relates wholly to course objective one and is a take home exam that is really is an exercise in researching information using the internet. Students are asked specific questions related to different technologies and companies and they need to do some digging to locate the data. It is somewhat surprising that some senior college students still do not know how to use search engines effectively. The general idea is to convince them that they can be self sufficient when it comes to learning (or relearning) information critical to their job. We use to ask students to research a topic and then present it to the class, but this turned out to be very time consuming and the quality of the material presented was over a wide spectrum, from almost worthless to excellent, so we discontinued this approach.

Course objective number three requires students to: Build the model (Objective 2) on the Z-402 3-D printer and re-digitize the prototype using a non-contact scanner to verify the geometry against the CAD model. The students have access to the 3-D printer for producing their parts. A number of formal lectures are devoted to the 3-D printing technology (Z Corporation) since this is the only additive system we have. In the course of these lectures, the class is given a demonstration of the machine and supporting equipment to get a better understanding of the technology. As far as building parts, a lot of time multiple parts are built in one printing session. In this case, the machine is run by the instructor, with the students standing by, watching the procedure. On rare occasions when only one part needs to be built, the instructor will instruct the student on the use of the machine.

The Z-402 printer "prints" parts in a bed of plaster or starch by spraying a layer of binder over an area representing the cross section. Each cross section ranges in thickness from .003 to .007 inches thick depending upon the material. This part then must be removed from the machined, depowdered and infiltrated. Depending upon how delicate the geometry is, the instructor or the student will perform this process. The parts are very fragile when green (freshly printed) and starch parts must be removed from the build box very soon after the printing process finishes, or the parts will become caked with unbound starch. Caked parts make the depowdering process a lot more difficult and it is easy to destroy the part and have to re-print it. Unfortunately, you have to break a number of parts to develop a feel of their strength when green. When time is of the essence, one cannot have students breaking parts when either removing them from the build box, or doing initial depowdering. It should be noted that when printing in plaster the opposite is true. The part benefits from being left totally incarcerated in plaster inside the build box, sometimes for days. The plaster material is given a chance to harden, and the unbound plaster does not have a tendency to cake on the part so removal and depowdering of plaster parts is easier. Building in plaster is usually reserved for thin wall, complex geometry while starch is used for simple, solid models. It takes the system twice as long to print in plaster, and it is also twice as expensive in terms of build material and other consumables such a print heads. After students had created a final print of their project on the Z-402 printer, they used the Roland LPX-250 scanner to generate a point cloud defining this final surface. They then import this data set into Pro/ENGINEER and by using Pro/VERIFY fit the scan data to the original CAD data. The software will display any variations between the CAD model and printed prototype. The Z-402 is only accurate to within one percent when building parts but in general, a close correlation is obtained. There have been issues with this Pro/VERIFY causing Pro/ENGINEER to shut down on the student or take a half hour of processing time to register a fit between the model and data set. Function that behaves normally on the instructors' office machine sometimes act differently in the labs. The reader will note that there is only a minor mention of this functionality in the course objectives, with good reason.

Course objective four, five and six require the students to create tool paths using Pro/MANUFACTURING, verify the path visually using Pro/NC-CHECK, post process these tool paths to create the appropriate G codes and execute them on a CNC Router. Pro/MANUFACTURING was introduced to the students in their junior level CAD class so they are expected to have a basic understanding on how to develop proper tool paths. Speeds, feeds and depth of cuts as well as cut step over are issues. These are material and tool dependent. Students generally don't really think too much about these parameters until they are actually sitting in front of the CNC Router, waiting for the machine to complete a process. At this time

they realize that decisions that they made previous to this point are now affecting them. Only one student has ever been able to produce tool paths and run multiple paths directly and have the part machined correctly with out having to re-create the paths. Every student thinks that all their headaches are over by the time they start generating these tool paths. Since machining the part is the last exercise they are going to perform, it comes right at the end of the semester, usually two weeks before graduation. At this point "senioritis" has started to set in as most (depending on the economy of that year) students have found a job and are not exactly enthused with having to do re-work to fix their mistakes. In future semesters the course needs to be changed such that some fairly critical surface geometry, tool path creation and fixturing exercises can be done mid-semester. Mistakes made at this point could be a valuable lesson for the latter part of the semester. This would be a good time for students to begin to understand and experience the differences between G0 (shared tangent or curvature across the boundary) , G1 (at every point along that boundary they are tangent to each other) and G2 (tangent continuous across the boundary) surface continuity if they could physically see these surfaces having machined them on the CNC Router.



Project Schedule:

The following is the last schedule to be used and the weighting of each deliverable. Note that the project is worth 50% of the course grade. 40% of the course grade was for singular lab and homework assignments, with 10% reserved for the final exam. Six weeks into the semester the students had to be to the point where they could create intelligent surfaces for their project.

Mile stone:	Date:	Points:
Project Approval	1/26	5
Clay Model	2/2	10
Digitize Model, Main body Surface	2/16	15

Word Document showing main surface (shaded) as well as datum curves

Final Surfaces, Model ready to print	3/3	20

One Word document showing all surfaces (shaded) and one detail drawing showing the principle views with overall reference dimensions. Note that the instructor needs to check the clay model against the detail drawing, so make sure you bring the clay model to class!

Z402/Clay model match	3/15	5
Laser Scan documentation	3/22	10

Documentation will be two pictures similar to those found on page 2 and 3 of the document titled "Scanning the Cell Phone on the Roland LPX-250 scanner".

Final Design with "detail"	3/31	5

A Z-402 model will be produced with this data.

Tool Path Documentation	4/14	15

Required: Roughing, surface and trajectory milling operations with tool changes.

Documentation: Screen images from VERICUT for each NC sequence (cumulative). Both top and bottom from split line.

Phoenix Router model	4/30	20

20 points maximum

Foam Model only	5 pts
Foam + MDF Model	20 pts

Total	100

Future methodologies for teaching surface modeling to be employed:

Pro/ENGINEER is sold by PTC, Inc. They include as part of the University Plus program access to training materials through their ProjectLink website. These training materials are the same ones used by their in-house staff to teach people in industry how to use various modules of Pro/ENGINEER. These include copies of PowerPoint Presentations, training manuals for both students and instructors as well as the appropriate files for use within Pro/ENGINEER. Review of the training manuals for traditional surfacing (548 pages) and freeform surfacing (486 pages) indicate that sections of these manuals would be a good fit for this course. The exercises are well written, extensively tested and have time limits specified. Since color is critical when viewing these documents, rather than requiring students to have a copy printed, the students should be able to simply access the document in pdf format in a separate window on the computer. Use of these two training manuals normally would require 40 hours of work. Students taking the 410 course would have already been exposed to some of the material in prior CAD classes and not all exercises in the manuals are appropriate to what is required in the course. There are about six hours of exercises that would be appropriate from the traditional surfacing manual and about seven hours of exercises from the freeform surfacing manual. Since each lab session is scheduled for two hours, roughly eight lab sessions, or about one half of the semester would be devoted to exercises on singular topics. The other half of the semester would be in applying these topics to the semester project.

Lab Equipment/issues and costs; initial and continuing.

The most critical piece of equipment required in any course dealing with Rapid Prototyping is the inclusion of an additive system. Being able to quickly produce a part that has been modeled using what ever software is at hand not only demonstrates the concepts, but allows multiple iterations of a product to be produced. We chose Z Corporations Z-402 printer, depowdering station and automated waxing station. When we purchased the product, the cost was about $40,000. The Z-402 has been discontinued and replaces with the Z-310 printer which is simpler and easier to use. The build size is the same (8" x 10" x 8") but the cost is around $30,000. It should be noted that there are on-going maintenance and consumable costs. We have a special abbreviated service contract where we pay $3000/year for phone and hardware support. Normal maintenance is $6000/year. For that price Z-Corporation will fly out a technician to fix your machine if the problem cannot be solved over the phone. In three years we have had three instances that we had to wait for parts (overnight). Z-Corporation provides training to allow you to fix most issues yourself, which we have done with no real problems. We have added an additional depowdering station that we built and a drying oven to speed up the post processing operation of parts. Other consumables for the printer are primarily binder ($250/gallon) and build powder ($180/500 cubic inches in starch and $350/500 cubic inches in plaster). Print cartridges are $85 each. The amount of binder, build powder and print cartridges consumed are a function of how much printing you are doing on the machine.

Data collection is another issue that must be addressed. There must be some way of getting data from the machine to a file to be used down line, so existing coordinate measuring machines you might have may or may not be useful. Since we are dealing with highly convoluted surface geometry, we decided that a Microscribe 3-D digitizer, roughly $3000 coupled with Rhinoceros software would be adequate for collecting discrete data points. We purchased a Roland LPX-250 Laser Scanner for about $8500 for generating point cloud data.

For doing subtractive operations, we needed to get away from using the CNC Bridgeport that we shared with our technicians who work on molds and inserts for our Plastics Technology Program. We purchased a Phoenix CNC Router from a nearby outfit and it turned out to be somewhat of a mistake. The router was bought before we had an additive system. It was relatively inexpensive ($17,000), and it was a way (at the time) to get our students off the Bridgeport. The size (36" x 24" x 7") was simply a function of the fact that a large scale system was only a few thousand dollars more than a smaller machine. What we didn't know was that the company was going to go bankrupt six months after they delivered our machine, and that the larger system was highly under designed for its' size. The larger machine uses a bigger gantry. More mass with small servo motors results in over heating problems when running tool paths that require run times over one hour. Replacing the servos with larger ones fixed that issue. What it doesn't fix is the fact that the vacuum hold down table has warped badly and that the timing gear/ball screw arrangement is undersized and wears rapidly causing circles to appear as ellipses. There is move to turn this equipment over to the IET labs where it can be used to machine simple wood patterns for castings and to replace it with a HAAS Minimill ($30,000) that has roughly the same work envelope as the Z-402 printer and can machine aluminum, which is necessary for a similar type class titled Rapid Commercialization being taught in the Plastics Technology program.

Equipment use by other students: Senior Design and General class work

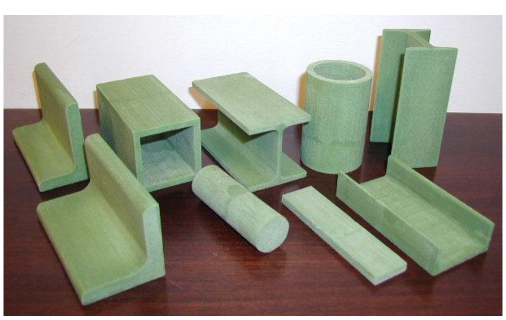
The Z-402 printer is used by students in other classes, some not even related to CAD. There have been requests by students for models for theater classes, prototypes to include with funding proposals to SGA and parts made in conjunction with students' speech classes. It is the students' responsibility to build the CAD model and to have the model reviewed with the faculty member in charge of the 3-D printer to make sure the model is of such geometry that it can be printed. Students who do an exceptional job of designing a product in a CAD class often request that a physical model be produced to further document their work. Senior design students have produced parts for wind tunnel testing and for demonstration parts of designs for the industrial sponsors

Array of cooling fins (.030" thick x 2.4" diameter X 24" long)
in wind tunnel – Senior Design project

Equipment use by faculty

CAD instructors occasionally request part sets to be used in their CAD classes. Rather than simply having the students work from an isometric, a 3-D model of the part can be used in a class exercise. The printer is fast and inexpensive enough to run so multiple parts can be produced with little effort. Faculty have used the capabilities of the printer to produce wind tunnel models. One faculty member is doing research on sailboat spinnaker shapes, so he had a series of models built to be run in the wind tunnel.

Demonstration Models for Statics Course



Spinnaker Models for Wind Tunnel

Equipment use by local industry

Outreach to the community and specifically to local industry is encouraged by the university. By printing parts for companies we have been able to educate them in new technologies such as rapid prototyping. The policy is usually to bring engineers and managers in from a company, discuss the benefits of the specific technology and talk about the pros and cons of our particular system. We will then build a part for the company at a minimal charge. There have been times that these companies have come back to us and asked us to build additional part, which we have done at slightly increased rate. If the company comes to us again for additional parts, we give them a list of service bureaus whose business is making rapid prototypes as we do not provide this service commercially.

Prototype Impellor

General Teaching and Research Opportunities

A survey was conducted relating to current trends and issues in the profession of graphics education by Clark and Scales in 1999 and followed five years later by a follow-up survey. (Clark, Petlick and Scales, 2004).(3) In the follow-up survey, a question was asked concerning main topics of research needed in the field. Responses included "reverse engineering in industrial and medical applications", "rapid manufacturing technology", "simulation and reverse engineering", and "rapid product development"(4) It is interesting to note that material in METBD 410 covers all the responses listed above. This suggests that not only does the instructor need to be well versed in the technology in order to teach the course, but the student is being exposed to the latest technology in the field. For a faculty member looking to expand their research interests with an emphasis of being able to directly apply it to the learning environment, the area of rapid prototyping is an ideal fit.

Summary

A Rapid Prototyping class and laboratory is an excellent way to offer an advanced CAD course to students interested in advancing their CAD expertise beyond what is required in the core curriculum. Such a course is challenging to teach as it requires students in a Mechanical Engineering Technology program to develop skills that are not necessarily required for designing machine parts. Proportions, an eye for a fair surface and the appropriate CAD skills to produce such geometry take time and practice. The students also have an opportunity to apply prior skills, such a creating and running tool paths on complex surface geometry that they have generated. The students get educated in emerging additive system technologies and if the lab is adequately equipped, other students, faculty and local industry can benefit from this facility.

The entire METBD 410 course, with syllabus, lecture topics, lab assignments and four years of project assignments are located at
http://engr.bd.psu.edu/METBD_410/METBD_410/main_410.html
This is not password protected. From May through August all links are active. During the semester, links to labs before the current date would be inactive.

1. Ogando, J., Goodwin, A. (09/08/03). “Fast Models, Big Value”. *Design News.* Reed Business Information, Highlands Ranch, Colorado.

2. Virtual Reality and Rapid Prototyping Lab, University of Missouri-Rolla, Retrieved January 3, 2005 from http://web.umr.edu/~vrpl/proj-rp.htm

3. Clark, A.C, Petlick, J.H. & Scales, A.Y. (2004). A Study of Current Trends and Issues for Graphics Education: Preliminary Results from a Five-Year Follow-up Survey. *Published Proceedings of the American Society for Engineering Education 59th Annual Midyear Meeting*, Williamsburg, VA.

4. Ibid

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