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Integrating Rapid Prototyping Technology into the Curriculum

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Introduction

In 1987 the manufacturing industry was introduced to an emerging new technology called rapid prototyping at the AUTOFACT show in Detroit. At that time it was referred to as stereolithography and the prototype was produced by curing photosensitive polymers with an ultra-violet laser. Since then many other forms of rapid prototyping technology have been introduced to the marketplace (Winek & Vedaraman, 1995).

From 1987 to 1997 the annual unit sales of rapid prototyping systems exceeded the 1000-unit mark (Wohlers, 1998). Some experts predicted that rapid prototyping would become a billion dollar industry in 1999 (Wohlers, 1997). Today there are conferences, publications, and associations available to support this growing industry.

There is a growing acceptance of rapid prototyping because of its capability to reduce the time-to-market cycle of new products (Hosni, Nayfeh, & Sundaram, 1999). What once was considered technology for only the aerospace and automotive industries is now becoming more commonplace in the government/military, academic institutions, and industries such as business machines, consumer products, and medical (Wohlers, 1998). Rapid prototyping applications include concept models, master patterns, functional prototypes, and tooling (Rapid Prototyping Association, 1999). Experts point out that rapid prototyping has changed the nature of how products and tooling technologies are developed to a fraction of the time it took previous technologies to do so (Rapid Prototyping Association, 1999).

Over the years companies have invested in computer numerical control (CNC), computer-aided design (CAD), and other automated technologies to improve their market share and profitability. Gradually industrial technology departments integrated these technologies into their curriculum. In recent years this has also begun to happen with rapid prototyping technology due to the industrial demand. This article will review important aspects of rapid prototyping technology and relate how this technology has been integrated into the Department of Industrial Technology Curriculum at Illinois State University.

Definition and Purpose of Rapid Prototyping

Wohlers (1998) defines rapid prototyping as "the physical modeling of a design using a special class of machine technology" (p. 953). The design typically is produced using a CAD system to create the model, and another device to create the prototype. Compatible software and hardware are key ingredients to producing good prototypes and models.

Many firms find that the design of a product often drives a high percentage of the manufacturing cost (DuVall, 1996). Rapid prototyping can help reduce some of these costs by providing concept models and prototypes within hours or days once the three-dimensional (3D) model is created. This allows anyone involved in the design process to view an actual representation of the end product to identify discrepancies and problems quickly. Functional prototypes can be produced and even subjected to certain types of tests like assembly checking. This can be a very efficient means of verifying a design before going to the expense of producing a production part or mold.

The functional prototype can also be used for sales and marketing purposes. Customers can be given the prototypes to provide feedback on the product before production begins. Discrepancies that are found can be modified and the design can be optimized in the pre-production stages. In today's market, this can prevent devastating loses in sales after a product is introduced. Sales and marketing people can also use the prototype to sell the product and write orders prior to production (Wilson, 1996).

In the educational setting students should be introduced to rapid prototyping so they will be familiar with the technologies involved and the advantages that they provide companies. Rapid prototyping should not be a stand-alone experience or course but an integrated activity to allow the students to realize how it can benefit several groups in the design/manufacturing cycle. It is another technology that should be part of the student's professional toolkit similar to CAD, CNC, etc. Rapid prototyping can help them take a concept beyond the design stage of a 3D model to the point of an actual functional model in less time than machining. Rapid prototyping can also allow them to design more freely, especially when producing complex parts that are often difficult to produce through traditional machining methods.

The Rapid Prototype Method Used

There are several different rapid prototyping systems available to industries today, including, but not limited to, fused deposition modeling, laminated object manufacturing, selective laser sintering, solid ground curing, stereolithography, and multi-jet modeling (Rapid Prototyping Association, 1998). These technologies are often referred to as high-end systems, and are capable of producing a functional model. Depending on the type of rapid prototyping technology, concept models and prototypes can be produced from plastic, wood, ceramic, or metal materials. These materials are processed in a variety of different forms, such as liquid, powder, and sheet stock (Wohlers, 1997).

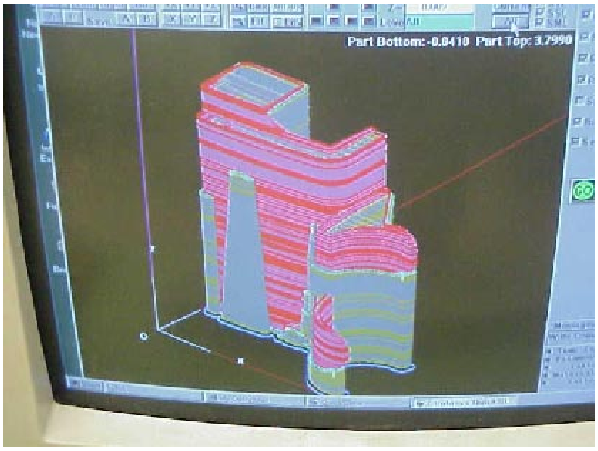
The rapid prototyping method used in the author's department is classified as fused deposition modeling (FDM). Like most rapid prototyping methods, this system receives the model geometry data from CAD models, and transforms the data into machine code for the prototype machine. The 3D model is exported from the CAD software as an "stereolithography" (STL) file, which is common to the field, and compatible with the proprietary software used with the FDM machine. The STL file is imported into the FDM software, Quickslice, wherein the model can be oriented, scaled, duplicated, or adjusted to fit within the work envelope of the FDM machine. The Quickslice software is used to slice the 3D CAD model into layers of a designated thickness. The software also calculates support material for parts of the model that are suspended in space, such as overhangs or horizontal slot surfaces. The slicing, support calculations, and layers are all visible on the screen as the software completes the process. The software also allows the operator to design additional support materials for helping process the FDM model when it is being created within the machine. The sliced 3D CAD model and the support material structure, as layered tool paths, are saved as a propriety format "manufacturing" file (SML) with the Quickslice software. The SML file is then downloaded to the FDM machine to create the model.

The FDM prototype is produced by processing one layer of plastic at a time, each compiled of contours and roads that are created much like a hot glue gun would lay down a bead of glue. The software pre-determines how the rapid prototype model layers will be constructed. The plastic used in the FDM at the authors' department is Acrylonitrile Butadiene Styrene (ABS) and costs approximately $25 per pound. The material comes in the form of spools of plastic wire, and the plastic wire is fed into a melting head with dual tips, one for the model material, and one for the support material. The head purchased with the model 1650 Stratasys FDM machine at the authors' department was designed specifically to be used with ABS plastic. Additional "heads" would need to be purchased to be able to make prototypes with additional materials. As the plastic filament is fed through the head, it is melted and then feeds out the nozzle to deposit the beads that create the layers. The plastic filament feeding process resembles the method in which a wire feed works on a gas metal arc welder. Figure 2 shows the melting head layering the plastic and building the prototype. The model is built on a foam base. One nozzle on the melting head layers the support material to hold the model while it is built. Another nozzle supplies the plastic that is the rapid prototype model that is being created. Once the model is completed the support material is broken away from the rapid prototype model.

Rapid Prototyping Applications in the Classroom

At Illinois State University the fused deposition modeler is used in several classes that are part of the Integrated Manufacturing Systems Sequence. Students are introduced to 3D modeling and rapid prototyping in IT212 Machine Design and IT216 Computer-Aided Design and Drafting (CADD). They are shown the process of slicing the models and creating STL and SML files. The instructor sets up the FDM machine and creates the rapid prototype for the

***Figure 1*. Picture of a sliced 3D model.**



students. The number of prototypes the instructor will create for the students is limited due to the costs and time involved. Figure 3 shows an example of a rapid prototype part designed by a student in one of the classes.

The instructor also runs parts on the FDM machine for students in a 300 level course entitled Industrial Production. The industrial production course is often referred to as the "capstone" course for the integrated manufacturing sequence because students are required to take this course or a professional practice experience. The course is taken mainly by seniors and is expected to be a culminating experience to the manufacturing sequence. It is a 4 credit hour course that meets for 3 hours twice a week. A minimum time commitment of 160 hours (includes time outside the scheduled class time) is expected from each student for the semester.

One assignment the students are given in the capstone course deals with the management aspects of rapid prototyping that they may face on the job. They are divided into groups and each group is assigned a specific rapid prototyping technology to research. Through a simulated assignment, they are told that the company for which they work has decided that it wants to purchase a rapid prototyping system to produce its own prototypes much faster. Each team has been directed to research a specific rapid prototyping technology and report back to the management so a decision can be made with regard to purchasing the appropriate technology for the company's needs. In this assignment each team is expected to address the following items:

1. Describe and explain the rapid prototyping technology your team is researching so the management better understands what it is and how it works.
2. Identify vendors along with their addresses, phone numbers and email addresses.
3. Identify the different models of machines that are sold, optional equipment and costs.
4. Identify any additional costs such as materials, maintenance or service contracts, upgrade costs, computers, software, firmware, training, travel, delivery, installation, and rehabilitation of the existing facilities.
5. Identify the power requirements to make the system operable.
6. Is this technology feasible for this company?
7. What are the risks involved in investing in this technology?
8. Are there unintended consequences?
9. Can we live with them?
10. Is this approach acceptable in this organization's culture?
11. Which company and model of equipment is judged best of those available?

Each team is expected to prepare a written proposal and present their findings to the rest of the class. This gives the students a good idea of what types of prototyping methods are available and what kind of project they may encounter on the job.

Another major component of the capstone course involves having teams of students work on projects for real clients. Since 1994 students in this course have completed projects for 4 different affirmative agencies and three different private manufacturing companies. The affirmative agencies subcontract with private service and manufacturing firms to maintain revenue-generating manufacturing facilities to employ or train people with disabili-

***Figure 2*. Picture of the FDM nozzles and the prototype being created.**

***Figure 3*. An example of a rapid prototype designed by a student.**

ties. The affirmative agencies are non-profit organizations that assess people's capabilities and then provide job training and employment for those who have physical and developmental disabilities.

The projects completed by the students in the industrial production class mainly consisted of process improvements. These are improvements that the organizations would like to have completed, but do not have the time, personnel, or money to invest in developing a solution.

The projects often required that the student groups designed, prototyped, tested, and refined tooling. In some cases, they subcontracted with groups of students in other classes who were responsible for producing portions of the prototypes (i.e. a control system). Each group in the capstone course was given time to assess the problem and then develop a written proposed solution. The proposals were presented and evaluated by a review panel consisting of the class, representatives from the agencies or companies involved, and the instructor. Once the proposals were approved, the students began further planning of their projects and production of a prototype.

As part of their assignment, the students were required to rapid-prototype parts in their design which were good candidates for this process. This caused the students to think about what type of parts are best prototyped through the fused deposition modeler and which might be prototyped better through some other method. Once the students created their 3D models, they met with the CAD instructor to use the software to slice the 3D model and had the CAD instructor run it on the FDM machine similar to contracting with a service bureau or a model shop.

Complete coverage of all the projects completed in this course over the years would be beyond the scope of this article. Therefore, two prototypes will be shown as examples. Figure 4 shows an example of an adjustable bracket designed to be used on a rack that held brake and fuel line tubes. The racks were transported through a furnace holding the product while the heat from the furnace sealed the plastic to the metal. The company wanted to reduce the number of racks it had to use for the different lengths of product and shorten the time it took to change over the racks. By producing a functional adjustable bracket, the students could actually test the designed part on the rack to verify its functionality. In addition, the students were able to verify the tooling and fixturing required to mill the part from aluminum stock. They were especially concerned about the T-slot mill cutter being able to reach to the depths that were required. With the functional prototype, they were able to verify this with the cutting tool and milling machine.

Figure 5 shows a link and sprocket, which were both part of an automated storage and retrieval design. The sprocket was an unusual shape and the students wanted to prove that the concept would be compatible with the other parts on the system.

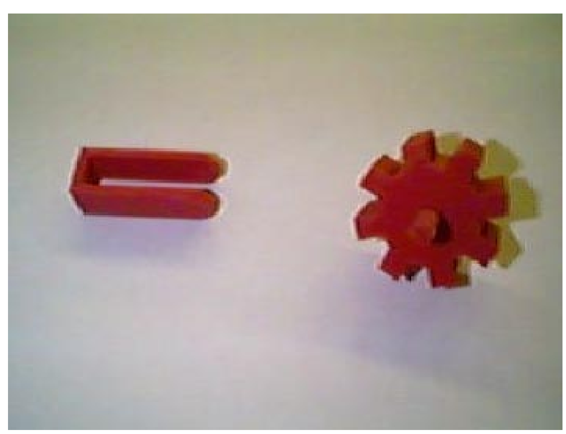
Approximately every 3 weeks each group had a review session to update everyone on the review panel with regard to the progress of the projects and to evaluate student performance. The students were able to bring the prototypes to the review session when they were completed to verify their design with the review panel. Decisions to alter or refine the design were made by the review panel similar to what might be encountered in industry.

Lessons Learned

Students need to have a good understanding of CAD software and 3D modeling to complete a rapid prototype well. Additionally, they need to understand the best way to orient the

***Figure 4*. Adjustable bracket for an oven rack.**

***Figure 5*. A prototype of a link and sprocket design.**



model so the fused deposition layers will build a quality part. The layers of plastic form a more accurate part and fuse together better from one direction than another, depending on the shape of the part. This can be especially true with parts that have thin cross-sections. Also, intricate parts with features less than .010" in size can become troublesome for the FDM technology.

Sometimes it is difficult to get the students to realize the need for both well-dimensioned orthographic projections and 3D models. Often the students wanted to skip over the orthographic projections and concentrate more on the 3D model. The students learned that orthographic projections are very useful in checking the prototype to verify the sizes and shapes.

Some groups made poor choices with regard to the parts they selected to prototype. They chose parts that didn't need to be prototyped or that could have been prototyped more easily with other methods. Students can become engrossed in the technology and lose sight of the practicality of what they are doing. It is important for them to understand when it is appropriate to use rapid prototyping and when not to use it. The software helps with this decision by giving them an estimate of the amount of time it will take to prototype a part. They can then calculate the costs involved and determine if it is justifiable to run the prototype.

In the capstone course it was difficult to get the students to finish the prototype at the time when it would have been most useful. Sometimes they ran behind schedule and the project proceeded ahead of the prototyping. With a semester-long course where there is an urgency to actually build a prototype, it is important to start the students out early on the 3D modeling and rapid prototyping. Some of the students had not taken the appropriate CAD courses since they were electives in the curriculum under their catalog. This caused them to rely heavily on the students in the class who did have this background and it magnified the problem.

Summary

Manufacturing companies are trying to reduce their time-to-market and to achieve concurrent engineering. Rapid prototyping has the potential to help the manufacturing industry achieve its objectives. As manufacturing companies become more successful in meeting their objectives, they can reduce their costs and increase profits.

To meet the needs of industry, rapid prototyping should become an essential part of the design/manufacturing curriculum in an industrial technology program. Choosing appropriate software and hardware is critical in providing students with current and essential knowledge with regard to rapid prototyping. The next step is to effectively integrate these technologies into the curriculum. There are conferences, seminars, publications, and newsletters to help faculty learn more about rapid prototyping and integrate it into the curriculum. Faculty in industrial technology programs have an obligation to their students and the manufacturing industry to meet this challenge.

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