AC 2012-3052: PREPARING TO USE RAPID PROTOTYPING: LESSONS LEARNED FROM DESIGN AND MANUFACTURING PROJECTS

Dr. Hung-da Wan, University of Texas, San Antonio

Hung-da Wan is an Assistant Professor of the Mechanical Engineering Department and the Director of Machine Shop of College of Engineering at the University of Texas at San Antonio (UTSA). He has been teaching undergraduate and graduate courses in the areas of computer integrated manufacturing systems, Six Sigma and lean methodologies, and manufacturing systems engineering. He also manages two rapid prototyping systems at UTSA. His current research interests include sustainability of manufacturing systems and web-based applications in manufacturing.

Mr. Firasath Ahmed Syed, University of Texas, San Antonio

Syed Firasath Ahmed is a master's student in advanced manufacturing and enterprise engineering at the University of Texas, San Antonio. He is a Graduate Research Assistant and helps with 3D Printing needs that arise in the Mechanical Engineering Department. He has experience in working with two rapid prototyping machines present in the university namely "dimension SST 1200es" and "Z Printer ZP450." He received his B.S. degree from Osmania University, India, in 2010. His research interests include rapid prototyping, manufacturing engineering, system simulation, and lean systems.

Preparing to Use Rapid Prototyping: Lessons Learned from Design and Manufacturing Projects

Abstract

Rapid prototyping (RP), also known as 3D Printing, has gained an important role in engineering education. It can be used to fabricate mechanical designs in a timely manner and hence is useful for design and manufacturing courses. In fact, many higher education institutions now have RP machines for research and teaching. Current literature reports that involving RP in design and manufacturing courses can significantly enhance active learning by providing quick and direct feedback on their designs via prototypes. In some cases, functional mechanical components can be made directly, which is especially useful for capstone design projects.

While RP has become a beneficial addition to engineering curricula, it can also be a burden to the instructors and students. In engineering, RP is typically introduced with an emphasis on the special features it can provide (e.g. freeform shaping and direct manufacturing), while the limitations and practical issues of RP often do not receive equal attention. Without a proper preparation, students' knowledge about RP can be superficial or even incorrect. As a result, students often overlook the constraints and fail to use RP appropriately.

This paper investigates the use of RP in design and manufacturing courses with a focus on preparing students and instructors to use the technology properly. With the experience of managing two different RP machines (i.e. fused deposition modeling and 3D printing), the authors have documented a collection of failures of student projects involving RP. The causes of failure have been categorized into *Dimensional, Functional, Operational,* and *Economical*. Finally, a guideline is provided for preparation of using RP in design or manufacturing courses in hopes of helping the readers create a more enjoyable and effective learning environment.

Introduction

In recent years, an increasing number of engineering educators have adopted Rapid Prototyping (RP) as a tool to enhance engineering curricula. Commonly known as 3D Printers, RP machines are capable of making three dimensional objects quickly and in an intuitive manner. Various technologies are currently available to deliver prototypes quickly[1]. The mainstream of RP technologies uses an additive manufacturing process that accumulates layers of material to form a three-dimensional prototype. This additive process "grows" a prototype directly from bottom up, instead of cutting one out of a solid block of material. As a result, RP does not require complicated process planning or tool selection. Thus it is an excellent tool for students with little manufacturing experience to fabricate their designs. Another significant feature of RP, enabled by the layer-adding process, is the capability to perform freeform fabrication. RP is capable of building almost any geometric design within the size limits. Additionally, many new RP machines can fabricate prototypes in color. All of these features combine to make RP a powerful tool for visualization of conceptual designs.

Active learning has been recognized as an important instructional method for engineering education. The core elements of active learning are student activity and engagement in the learning process[2]. In a traditional engineering design course setting, students do not typically have the opportunity to fabricate a design within a semester-long course, especially when the course is early in the program. RP provides an option for students with little experience or knowledge of manufacturing to fabricate a design in a timely manner. The ability to prototype a design rapidly allows students to carry out iterations of designs with quick and direct feedback and hence creates an active learning environment[3]. Consequently, RP gained an important role in engineering education, especially in design and manufacturing subjects. Many universities and even some high schools have installed RP machines for educational purposes. The positive impacts of RP on the learning experience will be discussed in the next section.

Despite the advantages of RP, an experienced user would know that managing an RP system for an educational program can be very challenging, especially when students are involved. With excitement about the new technology, students often focus too much on the good features and ignore the limitations and weakness of RP. As a result, the authors have experienced several issues with the involvement of RP in student projects. Some of these were minor problems, while some were catastrophic. These problems became important lessons for dealing with RP in practice.

The main objective of this paper is to discuss the lessons learned by the authors in hope that the experiences will help educators use RP in a positive and enjoyable way. In this paper, a summary of failures of using RP in student projects is provided, followed by a suggested guideline for avoiding the identified issues. Table 1 shows a summary of the issues discussed in the later sections.

Table 1. Summary of issues of RP in manufacturing and design projects

Categories	**Issues**
Dimensional Issues	• Size limit • Fine details and thing parts • Surface smoothness • Material trapping • Tolerance for assembly
Functional Issues	• Required strength • Made for assembly • Other potential functional issues
Operational Issues	• Setting up a job on computer • Physical preparation of a print job • Post-processing and leaning • Maintenance of RP machines
Economical Issues	• Necessity for using RP • Material usage • Build time and availability of equipment

The failure cases discussed in this paper are results of using two different RP machines owned by the institution where the authors serve. One RP machine, the Dimension SST1200, uses the Fused Deposition Modeling (FDM) technology, which extrudes a plastic filament to form the prototype. The other machine is ZPrinter 450, which uses the 3D Printing (3DP) technology that injects tiny droplets of adhesive and ink into plastic powder to form the prototype in color. The authors are the faculty supervisor and graduate assistant managing both systems. The two technologies have caused different problems, which essentially broadened the scope of the authors' experience with RP. Due to the diversity of RP technologies, some of the items listed in this paper may not apply to other RP systems, although every attempt has been made to provide a guideline that is general enough for most RP users.

Rapid Prototyping in Engineering Education: A Review

RP has been one of the most popular technologies adopted by engineering programs in recent years. Since 1990's, RP has been used in engineering education to enhance design related courses[4]. It became an essential part of the design and manufacturing curricula, ranging from first-year design and drafting courses to senior-year capstone projects[5-9]. It has also been used in two-year engineering program[10]. RP is considered as one of the "new frontiers" of manufacturing education, along with 3D scanning and reverse engineering[11]. In order to address the emerging demand of RP technicians on the job market, Patton and Liu[12] developed "train the trainers" workshops. In addition to using RP in regular engineering curricula, Strzelect and Vavreck[7] reported using RP to support broader mission of the campus, including recruitment of engineering students through a middle school program and collaboration with an art school. The technology has opened a new window for engineering education and other areas.

The reason that RP became so popular in education is mainly due to the simplicity of its operation and the positive impact on learning experience. The benefits of involving RP in engineering education found in literature have been summarized as follows.

- RP was helpful in visualization and it presented a real-world application of course materials taught in class[10]. It closed the gap between theories and practices[13].
- Students gained improved comprehension of three-dimensional CAD models[4].
- In early courses, students use the RP models to communicate complex three-dimensional geometries and create working models of their concepts. For senior-year projects involving both design and fabrication, RP models are used not only during the design process but as functional components for testing[14].
- Students were not limited by their lack of machine shop fabrication skills to bring their designs to reality[5]. Compared to conventional fabrication methods, RP allows students to save the time and effort on fabrication and focus more on course contents[14].
- The speed and accuracy of the fabrication, the user-friendly design environment, the ability of the machine to produce complex parts, and the lightweight material are major advantages of RP, especially in the context of the senior capstone project[7].
- RP provided a way to conveniently produce one-off, technically complex artifacts required in many engineering courses[15].
- It allowed for a fast reiterative design approach and a short development time in student projects, leading to an increase in student's understanding and confidence[15,16].

- RP facilitates active learning projects where students can apply computer aided design, engineering, and manufacturing technologies with hands-on experiences[3].

While benefits of using RP were extensively discussed in the literature, one of the main purposes of this paper is to bring up awareness of the downside of RP. This paper is certainly not the first attempt of doing so. Stier and Brown[6] discussed the needs to prepare students well before using RP. The emphasis was on the orientation of parts, limitation of the thickness of intricate geometry, and whether it is appropriate to use RP when some parts can be prototyped easily with other methods. The limited application of RP parts as structural elements is also an important issue[7]. Regarding the practical operations, Sinha[11] states that cleaning and finishing (i.e. post-processing of FDM) is the most frustrating and labor intensive part of RP, and the manufacturing time can be significantly longer than a conventional machining process in some cases. Leonard and Street[17] discussed "the good, bad, and ugly" of using RP, in terms of student experience, implementation issues, applications, and outreach possibilities. They argued that, oftentimes, only the machine itself and not the whole process is considered, thus leading to difficulties in its implementation. The operations, material management, and dimensional errors are common issues to be addressed. In addition, Szydlowski[18] identified that a disadvantage of RP is that it can make impossible objects, which otherwise would be rejected by a shop manager. Therefore, the powerful features of freeform fabrication can also be a problem. Students should understand the manufacturability of their design when RP is not used in its mass production.

Important Facts about Rapid Prototyping

RP is indeed a powerful tool for engineering education. The most important advantages of RP (versus traditional prototyping methods) can be summarized as follows:

- <u>Rapid</u>: RP requires less planning and preparation compared to conventional manufacturing processes.
- <u>Freeform</u>: RP can build complex 3D geometry which may not be possible using single conventional manufacturing process.
- <u>Direct</u>: RP accomplishes a tight integration from digital files to numerical control. It eliminates the need of tool selection, tool path planning, and fixture design.
- <u>Economic</u>: RP does not need expensive dies and molds.

However, RP has its down side, too. The drawbacks are often overlooked by users who are not experienced with RP. Following is a list of the drawbacks in contrast to the good features.

- <u>Not Really Rapid</u>: Using a FDM machine to build a product with the size of a coffee mug can easily take more than 10 hours, not including several hours of post processing. The 3DP method is one of the fastest among RP systems, but it would still take 2 to 5 hours plus drying and post processing. Bigger and complex parts may take more than 40 hours to build by FDM.
- <u>Not Really Freeform</u>: RP has its limitation in freeform manufacturing. In general, thin and/or out-stretched structures may be too weak to build. Small holes may not come out correctly. Closed space would trap excessive or support material and cannot be emptied after it is done.

- Not Really Direct: There is always a setup process on computer, which involves orienting and packing multiple parts. Some machines require physical setup, such as installing a base plate for FDM. Many RP technologies require post-processing.
- Not Really Economic: It is definitely not cheap! The machine, main material, support material (if applicable), accessories, support equipment (e.g. tank or furnace for post-processing), and personnel training may all be costly.

It is worth noting that in most cases RP is still a very good (if not the best) option for student projects. A traditional prototyping process done by a machine shop typically takes 2 to 4 weeks, including design approval, process planning, tool selection, fixture selection and/or design, material procurement (if not on-hand), machining, additional processes, and possible reworks. Therefore, a 40-hour FDM process still can be a faster and more economic option, especially for student projects that do not require production-grade results in most cases.

FDM and 3DP systems are popular options for universities because of the affordable costs. The cases discussed in this paper are also based on these two technologies. There are several other RP systems on the market. Some of them deliver better dimensional and geometric stability and tolerances, and some are faster. However, since the authors do not have direct access to the other systems, the scope of the "lessons learned" is limited. In order to compensate that, Table 2 gives a quick comparison of some common RP systems. The exact measures (i.e., max part size, tolerance, etc.) may vary from model to model, so the table shows mostly relative ratings. More information about various RP systems can be found in the references[1,19,20]. It should be noted that different RP systems have different advantages and possibly different problems. Reports about other RP systems would be valuable for fellow researchers and educators.

Table 2. Comparison of common RP systems[1,19,20]

RP System	Material	Layer Thickness	Surface Finish	Freeform Capability	Cost	Post-Process	Build Speed
Stereolithography (SLA)	Liquid photopolymer	0.001"	Smooth	Excellent	High	Yes	Average
Fused Deposition Modeling (FDM)	Plastic Filament (ABS and limited options)	0.005"	Rough	Good	Mid	Yes	Slow
Selective Laser Sintering (SLS)	Powdered material with high diversity	0.004"	Average	Good	High	No	Fast
3D Printing (3DP)	Plastic powder (and limited options)	0.002"	Rough	Good	Low	Little	Very fast
Laminated Object Manufacturing (LOM)	Sheet paper (and limited options)	0.002"	Rough	Limited	Mid	Yes	Fast
CNC-based Prototyping	Diverse options	N/A	Smooth	Limited	High	No	May be slow

Issues of RP in Manufacturing and Design Projects

This section presents a collection of problems of using RP in student projects in engineering design and manufacturing courses. All listed cases happened between 2007 and 2011 at the university where the authors serve. Two RP machines (i.e. FDM and 3DP) were involved.

Details of some early projects were not preserved, but the main issues were noted in this section. In order to explain the issues systematically, they have been separated into four categories: *Dimensional Issues, Functional Issues, Operational Issues,* and *Economical Issues.*

(1) Dimensional Issues

Dimensional error of RP is one of the most researched issues of the technology. However, in practice, there are more problems than the accuracy of the machines. Some common restrictions of RP are: (1) Material Trapping: Loose powder, liquid, or support material trapped inside of an enclosed area, (2) Thin Structures: Thin parts can break easily in some RP processes, may cause warping of products, and may be impossible to be built with some machines, (3) Overhung or Out-stretched Structures: They may not be possible to build without deformation or breakage with some machines. Some of the problems have been documented as follows.

- **Size Limit**:
  Two cases were documented in fall 2011, in which the students ignored the size limit of RP. One senior design team had to divide their CAD model into two halves and design a connecting mechanism in between. Another student (independent study) shrank the design of the medical device for proof of concept.
- **Fine Details and Thin Parts**:
  The prototypes built by 3DP process are typically brittle and break easily. In an outreach program for K-12 students from 2008 to 2010, several objects were built using 3DP to showcase the advanced technology. Many features were too delicate, and the prototypes broke during or after post-processing. The results include a statue of liberty with a broken arm, jet fighters with broken wings, etc. as shown in Figure 1.

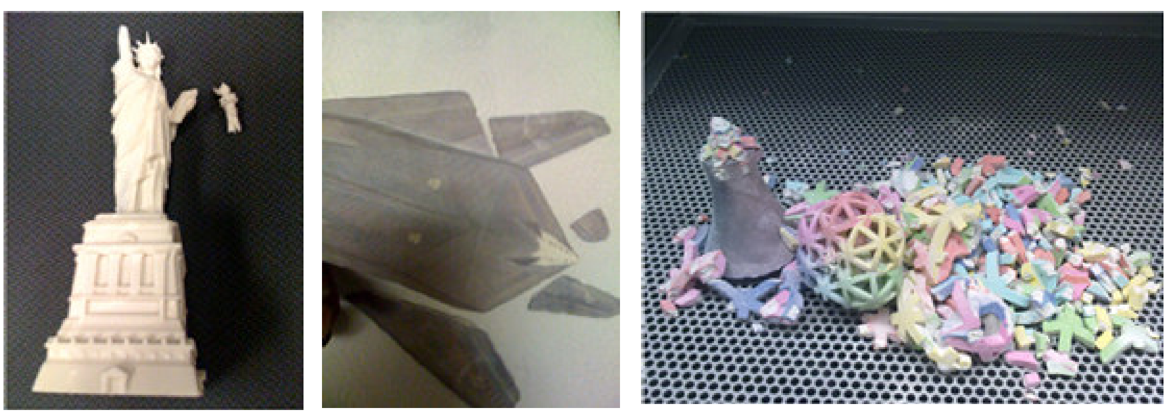


Figure 1. Broken 3DP prototypes due to weak structures

Products made by FDM process are much stronger. However, due to the size of the filament, delicate geometric designs may not come out correctly. In order to test the limit, the authors built two sets of parts with small pins (0.1mm dia.) and holes (0.1mm dia.). As a result, one pin was missing entirely. The other pin was crooked (Figure 2) and snapped a few days later. The small holes turned out to be much smaller than 0.1mm.

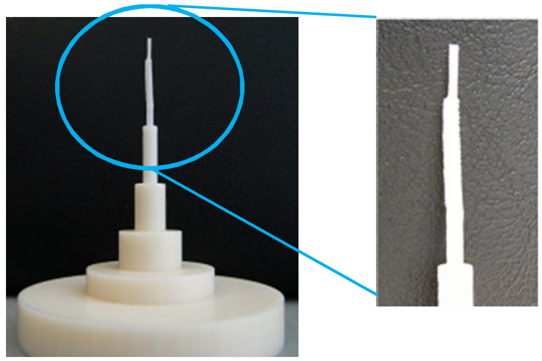
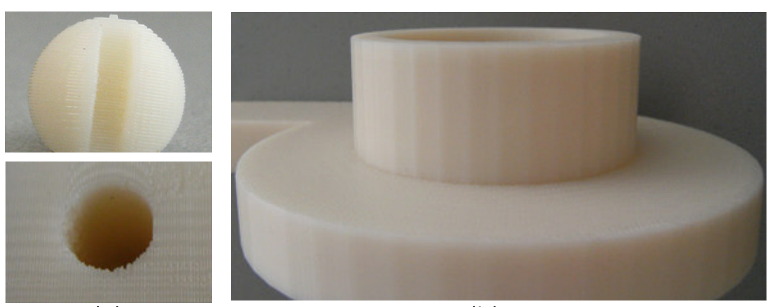


Figure 2. Fine details of FDM prototypes may not be made correctly

- **Surface Smoothness**:
  Different RP technologies have different capability of delivering the surface smoothness. Comparing 3DP and FDM, products of 3DP is smoother due to the fine size of powder as raw material. Several cases of rough surface of FDM products have been documented. Figure 3(a) shows that the slanted (or curved) surfaces of FDM products can be ragged due to the size of plastic filament that forms the layers. Figure 3(b) shows a different problem. The component of an air filtration system (senior design, fall 2011), which should be perfectly circular, came out with small edges that affected the airflow. It was caused by a low resolution setting when the students translated the CAD model into STL format (commonly used by RP machines). The STL format uses triangular mesh to approximate 3D designs. With a low resolution, the STL file is compact, but the approximation of curvatures can be rougher than expected.



(a) (b)

Figure 3. (a) Roughness of slanted or curved surfaces of FDM products; (b) Roughness caused by low resolution of STL file

- **Material Trapping**:
  Over the years, we have not seen any case of material trapped entirely in a closed space. However, there have been cases in which the support material of FDM products could not be removed completely after 10 hours of post processing. A deep blind hole would be the typical case where the soluble support material cannot be dissolved easily due to poor circulation of solvent. Figure 4(a) shows how support material resides in the products, and Figure 4(b) demonstrates that the efficiency of post-processing can be improved by adding openings to improve circulation of solvent.

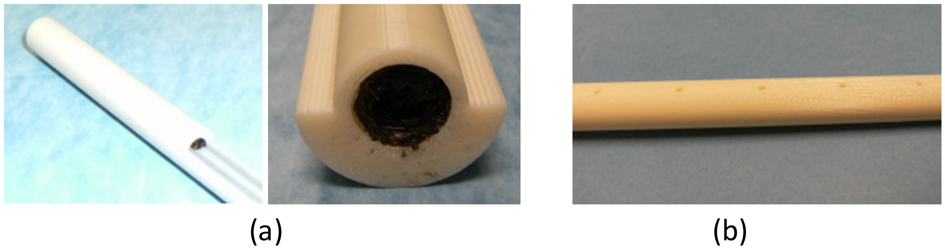


Figure 4. (a) Support material resides within tubes; (b) Adding openings can speed up the post-process

- **Tolerance for Assembly**:
  A few cases of senior design projects have encountered problems of FDM parts for assembly. When tolerances were designed too tight, any minor geometric inaccuracy can result in difficulties to fit the parts together. In all cases, the FDM products were sanded afterwards to give enough clearance. Sanding the surface is feasible as long as the top layer (i.e. the "wall" in Figure 5(a)) is not removed too much. The geometric accuracy of FDM products is generally acceptable for student projects. The main problem lies in the corners and the start/end point of a layer as shown in Figure 5(b).

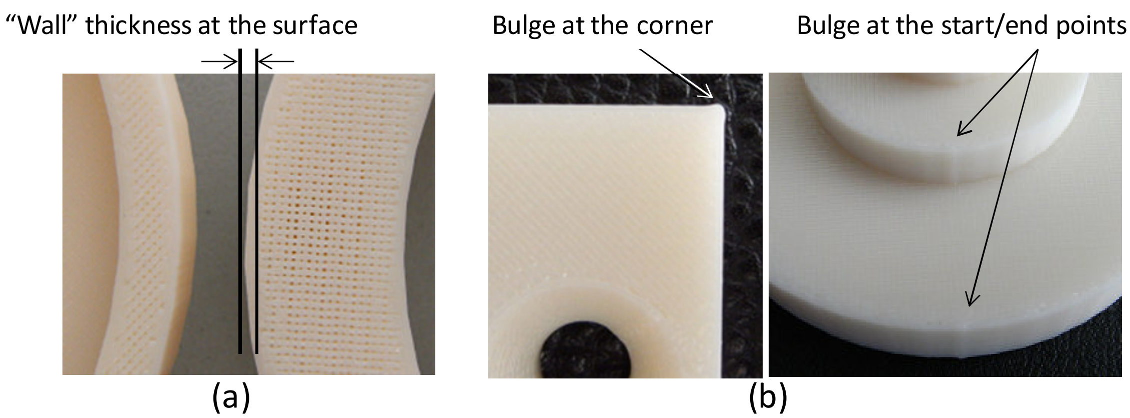


Figure 5. (a) Surface of FDM products can be sanded to a certain extent; (b) The corners and start/end point of a layer may bulge

(2) Functional Issues

This category reports the problems of RP products for functional use. The focus is on the feasibility and readiness of the parts for the expected functions. Some RP technologies are not designed to make final products with required strength or other properties. Students in capstone design projects sometimes do not realize that and thus make mistakes.

- **Required Strength**:
  As mentioned earlier, products of 3DP do not possess good mechanical property and break easily. Despite the weak points in a structure (Figure 1), the brittle products do not carry much tensile strength. Figure 6 shows a bolt that was broken when tightened. On the other hand, students sometimes overestimate the strength of FDM's ABS plastic products. The Society of Automotive Engineers (SAE) racecar team of our institute prototyped some FDM parts for the muffler in 2007. The parts broke due to vibration

during a test run. With the lesson, the team prototyped some more FDM parts in 2009 for air intake, which required little strength, and it was a success. Another case is that a senior design group in fall 2010 built a quad-copter with FDM parts to hold the motors. A few parts broke in every test flight, and the parts were remade several times.

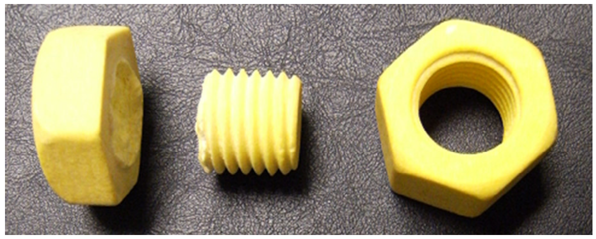


Figure 6. Broken RP parts due to lack of required strength

- **Made for Assembly**:
  As shown in Figure 5, dimensional errors can cause problems for fitting parts in an assembly. Additionally, the surface of FDM products is full of horizontal grooves, a result of accumulated layers. Making relative motion between FDM parts would be problematic if the contact faces have grooves perpendicular to the direction of motion. It usually can be resolved by sanding them, which takes more time. Furthermore, there are other problems that can affect the function of an assembly. The outreach program for K-12 technology experience designed a truck in 2010 with wheels that should turn freely. The 3DP product was post-processed by applying a special adhesive to the surface, and then all four wheels were glued to the car and would not turn as designed (Figure 7).

Figure 7. Wheels of the truck were glued and would not turn

- **Other Potential Functional Issues**:
  There are other potential functional issues that have been noted. The air filtration device shown in Figure 3(b) was not as smooth as expected. The senior design team suspected that it affects the efficiency of the filtration even though it works. Another potential problem is that neither FDM nor 3DP products are water resistant or airtight, even though they appear to be sealed. The designers must keep that in mind.

<u>(3) Operational Issues</u>

This category covers the problems caused by the poor operation or maintenance of the RP equipment. Some of them lead to longer build time, while some others damaged the machine.

- **Setting up a Job on Computer**:
  Setting up a RP job generally involves two stages: setting up <u>on computer</u> and preparing <u>the equipment</u>. The set-up on computer is mainly orienting and packing CAD models into the build chamber. As mentioned in many research articles, orientation of the RP parts is critical because it affects build time, usage of support material, and strength of the product. A senior design group in 2007 made a long, slim tube for a medical device. It was built vertically in the chamber, which made the build time significantly longer than building it horizontally. Also, it used a large amount of support material which could have been saved by laying it flat. In addition to orientation, packing multiple jobs into the chamber to build them simultaneously can save significant amount of time.
- **Physical Preparation of a Print Job**:
  The physical preparation of 3DP is relatively easy. With the FDM machine, a new base plate needs to be installed for every job. It is possible to reuse the plate if planned out carefully. However, the residuals of old material or a deformed plate can damage the extrusion heads of FDM. The authors experience the problem, and it was costly. Beside the plates, the filament should be checked for material deterioration before printing.
- **Post-processing and Cleaning**:
  This is the most criticized part of the RP technologies as reported in the literature. Different RP technologies require different post processes. For FDM, it involves dissolving the support material in a heated and circulated tank of solvent. In some cases, students left the parts in the tank for too long (more than 8 hours), and the parts deformed. For 3DP, the post process is to let the product dry, de-powder it, and apply a special adhesive to the surface. Oftentimes, the products broke during de-powdering process (Figure 1). Furthermore, even with an enclosed chamber, the powder can leak out to the floor and get into electronic devices nearby. Finally, students often leave drops and marks of the adhesive on the table, the floor, and other places. Proper protection and a standardized procedure are necessary.
- **Maintenance of RP Machines**:
  In addition to setups and cleaning, periodical maintenance of the machines needs to be done by designated personnel. The problems we experienced include: 3DP print head dried up, FDM filament left in machine and deteriorated, and FDM extrusion head worn out and could not build products correctly (Figure 8).

Figure 8. Failed RP project due to worn FDM extrusion head

<u>(4) Economical Issues</u>

Students sometimes do not realize the high cost of RP, and do not know how the process can be done economically by changing the print orientation, etc. A few cases are summarized below.

- **Necessity for Using RP**:
  Sometimes the senior design students would request to use RP before carefully examining the design, which results in additional iterations of prototyping. With modern CAD software, many tests and visualization can actually be done on computer without wasting the time and cost to prototype.
- **Material Usage**:
  The outreach program of K-12 technology experience built a small robot in 2009 that was solid inside. If it were hollow, lots of material and time could be saved. Besides, orientation can make a significant difference, especially when using FDM.
- **Build Time and Availability of Equipment**:
  Students often do not realize how long the build time can be. The senior design teams usually request for using RP at the end of the semester when several teams need to compete for the resource. As a result, qualified operators often need to work at night or during weekends, and delays occurred.

Suggestions for Preparing to Use RP in Education

The lessons learned from the past urged the authors to rethink about what to do and what not to do with the RP technologies. At the beginning, all senior design students were allowed to operate the FDM machine as needed. After a few hard lessons, the machine is now operated by a group of certified students under the supervision of the authors. And the authors have started offering seminars to students in senior design classes to get them prepared before they decide to use it. With better awareness and understanding of the technology, the cases of failure decreased and became less severe. Following is a guideline suggested by the authors.

(1) Job Preparation

Two checklists were developed for different groups of people to ensure the quality of each job. The designers (job requestors) and operators should go through the checklist for every job.

- **Checklist for Designers:**
  - Check the size: Is it too big? Is it too small? Is it in the correct unit system?
  - Check the shape: Check feasibility of delicate features, material trapping, potential roughness of slanted surfaces, and feasibility of post-processing.
  - Check the resolution of STL format.
  - Check the strength and functional requirements versus the capability of RP.
  - Specify orientation of printing, which affects time, surface roughness, material usage, and strength.
  - Check for chances to save materials (e.g., solid vs. hollow) and to improve efficiency of post process (e.g., more openings).
  - Check the availability of machine and schedule in advance.
- **Checklist for Operators:**
  - Check if materials in use are enough (including main material, adhesives, support material, etc.) for the current job.
  - Check materials inventory at the facility.
  - Check quality of materials being used.
  - Check availability of other accessories and tools for building and post processing.

(2) Equipment and Facility Preparation

The following items should be in place to ensure the readiness and availability of the equipment and facility.

- **Visual Standard Operation Procedure (SOP) for Machine Operators:**
  - Including how to set up, operate, and clean up, as well as emergency contacts.
- **Operations Log and Feedback/Report System:**
  - To document build time, material usage and inventory, defects and other issues.
- **Posting of Availability and Schedule:**
  - A mechanism to communicate with students who need to use the machine.
- **Preventive Maintenance Program:**
  - A mechanism of periodical checks and maintenance of key components, materials, accessories, and facility support functions.
  - Set triggers of maintenance by time, amount of materials, etc.

(3) Personnel Preparation

It is critical to bring the awareness and correct knowledge to people who may use this new technology. Two types of training are suggested:

- **Introduction to Students/Faculty/Staff:**
  - Provide introductory information to design and manufacturing classes and reach out to other groups through seminars and other channels.
- **Certification Program for Machine Operators (students and/or staff):**
  - Basic Level: Certified for regular job operation and reporting.
  - Advanced Level: Certified for maintenance and problem solving.

Due to the high cost and delicacy of the equipment, we do not recommend allowing students to use the RP machines freely. Encouraging students to get certified for using the machine is a better option.

Conclusion

Incorporating RP into the engineering curricula has many benefits; however, it can also create some potential problems. This paper aims to provide useful information for educators who have used RP or are interested in using it for design and manufacturing courses. By reviewing the hard lessons learned by the authors, the readers can save some trials and errors and enjoy the benefits that RP can provide. An important point is that everyone involved in the projects using RP should be educated and prepared for using it. In most of the failure cases documented in this paper, students learned about the new technology from fellow students and often did not fully understand its capabilities and limitations. Most of the advisors of the student projects were not directly involved in the use of RP, and not all of them were familiar with the technology. Therefore, it was concluded that bringing the awareness to everyone involved in the projects is essential. Through seminars given by the authors, the number of problems with the use of RP in student projects has been reduced significantly. Therefore, if planned well, RP would be a very good tool to be used in student projects in design and manufacturing subjects.

Bibliography

1. Grimm, T., 2004, User's Guide to Rapid Prototyping, Society of Manufacturing Engineers, Dearborn, MI.
2. Prince, M., 2004, "Does Active Learning Work? A Review of the Research," Journal of Engineering Education, 93(3), pp.223-231.
3. Lorenzo-Yustos, H., Lafont, P., Lantada, A. D., Nvidad, A. F., Sanz, J. L. M., Munoz-Guijosa, J. M., Munoz-Garcia, J., and Otero, J. E., 2010, "Towards Complete Product Development Teaching Employing Combined CAD–CAM–CAE Technologies," Computer Applications in Engineering Education, 18(4), pp.661-668.
4. Zecher, J., 1998, "Integration of a Rapid Prototyping System in a MET Curriculum," Proceedings of 1998 ASEE Annual Conference & Exposition, Session 3549.
5. Stamper, R. E. and Dekker, D. L., 2000, "Utilizing Rapid Prototyping to Enhance Undergraduate Engineering Education," Proceedings of the 30th ASEE/IEEE Frontiers in Education Conference, Session F3C, pp.1-4.
6. Stier, K. and Brown, R., 2000, "Integrating Rapid Prototyping Technology into the Curriculum," Journal of Industrial Technology, 17(1), pp.1-6.
7. Strzelec, R. A. and Vavreck, A. N., 2005, "Rapid Prototyping in an Electromechanical Engineering Technology Program," Proceedings of 2005 ASEE Annual Conference & Exposition.
8. Tester, J. T. and Wood P.G., 2008, "Assessing the Motivational Impact of Including Rapid Prototyping into a Freshman CAD Class," Proceedings of 2008 ASEE Pacific Southwest Annual Conference.
9. Lantada, A. D., Morgado, P. L., Sanz, J. L. M., Munoz-Guijosa, J. M., and Otero, J. E., 2010, "Toy Design Experience: Improving Students' Motivation and Results in a Final Year Subject," Proceedings of 2010 IEEE Education Engineering (EDUCON), pp.1481-1487.
10. Johnson, W. M., Coates, C. W., Hager, P., and Stevens, N., 2009, "Employing Rapid Prototyping in a First-Year Engineering Graphics Course," Proceedings of 2009 ASEE Southeast Section Conference.
11. Sinha, A., 2009, "New Frontiers in Manufacturing Education: Rapid Prototyping, 3D Scanning and Reverse Engineering," Proceedings of 2009 ASEE Southeast Section Conference.
12. Patton, K. and Liu, P. C., 2004, "Curriculum Development for Rapid Prototyping," Proceedings of 2004 ASEE Annual Conference & Exposition, Session 1526.
13. Kim, I. Y., De Weck, O., Nadir, W., Young, P., and Wallace, D., 2004, "Innovative Modern Engineering Design and Rapid Prototyping Course: A Rewarding CAD/CAE/CAM Experience for Undergraduates," Proceedings of 2004 ASEE Annual Conference & Exposition, Session 332.
14. Maletsky, L. P. and Hale, R. D., 2003, "The Practical Integration of Rapid Prototyping Technology into Engineering Curricula," Proceedings of 2003 ASEE Midwest Section Meeting.
15. Diegel, O., Xu W.L., and Potgieter, J., 2006, "A Case Study of Rapid Prototype as Design in Educational Engineering Projects," International Journal of Engineering Education, 22(2), pp.350-358.
16. Newcomer, J. L., 2002, "Using Rapid Prototyping to Teach Design for Automated Assembly Principles," Proceedings of the 32nd ASEE/IEEE Frontiers in Education Conference, Session F4D, pp.12-16.
17. Leonard, W. M. and Street, D. M., 2006, "The Good, Bad, and Ugly of Using Rapid Prototyping in Academics," Proceedings of 2006 ASEE St. Lawrence Section Conference.
18. Szydlowski, W. M., 2001, "Using a Rapid Prototyping Machine in the Integrated Kinematics, Dynamics, and Machine Design Lab," Proceedings of the 31st ASEE/IEEE Frontiers in Education Conference, Session S2E, pp.11-16.
19. Frank, M., Joshi, S. B., and Wysk, R. A., 2003, "Rapid Prototyping as an Integrated Product/Process Development Tool: An Overview of Issues and Economics," Journal of the Chinese Institute of Industrial Engineers, 20(3), 240-246.
20. Custompart.net, "Additive Fabrication," http://www.custompartnet.com/wu/additive-fabrication (accessed on March 4, 2012).

Appendix: Checklists for Job Preparation

In the appendix, the checklists for job preparation are reproduced as individual pieces of information that can be used directly by the readers.

<u>Checklist for Designers</u>: (Use this list for every job.)

- ______ Check the size of the design:
  - Maximum build size: W"xD"xH"
  - Scale: 1:1
  - Units: mm or inch?
- ______ Check the shape:
  - No thinner than T"
  - Holes no smaller than ϕ"
  - Feasibility of out-stretched and overhung structures
  - Roughness on slanted surfaces
  - Material trapping and feasibility of post-processing
- ______ Check the resolution of STL format.
  - Low resolution of curvature may cause roughness.
- ______ Check the strength and functional requirements versus the capability of RP.
- ______ Specify orientation of printing.
  - Affects time, surface roughness, material usage, and strength.
- ______ Check for chances of improvement
  - To save materials (e.g., solid vs. hollow)
  - To improve efficiency of post process (e.g., more openings)
- ______ Check the availability of machine and schedule in advance.

<u>Checklist for Operators</u>: (Use this list for every job.)

- ______ Check if materials in use are enough for the current job.
  - Including main material, adhesives, support material, etc.
- ______ Check materials inventory at the facility.
- ______ Check quality of materials being used.
- ______ Check availability of other accessories and tools for building and post processing.