A STUDY OF RAPID PROTOTYPING FOR USE IN UNDERGRADUATE DESIGN EDUCATION

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ABSTRACT

Development and use of rapid prototyping (RP) has drastically expanded in the last 10 years. Although use of the technology has been predominately focused in industry, academic use has become somewhat prevalent as well. At the U. S. Air Force Academy we have been using RP to enhance our design curriculum for the last three years. In this paper we give a brief overview of RP technology, and discuss how we use both classical (non-rapid) and rapid prototyping in our design classes. Assessment results from both faculty and students are presented which provide insight into the role of RP in undergraduate education. This assessment shows that students have an initial reluctance to using the RP technology. However, after they have used RP, they report that the process is surprisingly easy. In addition, they report that prototyping significantly enhances their design and more importantly, enhances their learning of the design tools and methodologies taught. Additional, more detailed, results concerning the use of RP are reported in the paper. Finally, we provide conclusions that indicate on how other institutions might use RP technology in their design curriculum.

1. INTRODUCTION

Rapid Prototyping, as defined by Cooper[1], is the layer-by layer fabrication of 3-d physical models directly from a computer aided design (CAD). For the last three years we have been using a rapid prototyping (RP) machine to facilitate design education at the US Air Force Academy. The specific type of RP technology we have employed is often referred to as a 3-d printer and is described in more detail in a following section. The RP technology has been used to enhance two of our courses in particular: 1) Sophomore Introduction to Design (ME 290) and 2) Senior Intercollegiate Design Competition Teams (ME 491 and ME 492Z). A photo of the RP machine we currently use (figure 1) as well as some items made with the RP technology (figure 2) are shown below.

This paper reports on a variety of different aspects regarding our use of the RP technology to enhance our design curriculum. First, we report briefly on current RP technology and how it fits in the design process. Next, we show how RP fits into the design process. Then, we elaborate on specific ways we have used the RP technology to facilitate our design classes, to include: exploring interfaces between different subsystems in a design, investigating human factors issues and aiding in the brainstorming process. Also, differences between RP and classical (non-rapid) prototyping techniques used in our classes are discussed and evaluated. In this context

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we provide specifics on issues like scaling, level of detail in the prototype as well as time and cost comparisons. Other specific advantages and disadvantages of using RP technology in undergraduate design are given as well. Finally, we show our assessment results, which have been obtained both from students and from faculty. Overall, the assessment from students indicates that use of the RP technology has helped them uncover significant errors in their initial conceptual design. However, due primarily to the perceived difficulty in constructing the rapid prototype, there remains considerable resistance to creating them. Interestingly enough, once the students have used the RP technology, they report that it is NOT difficult to use. Faculty feedback on the RP use has ranged from negative comments on the cost of the parts and on the RP limitations to positive comments on the overall experience for the students in terms of exposure to current design tools and enhancement of the design process made available by the RP technology. Specifics from our assessment study are reported below in the paper.

Figure 1
Stratasys Rapid Prototyping Machine (3-D printer)

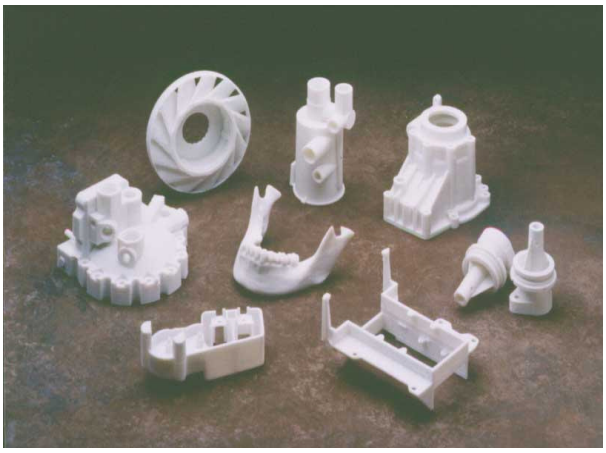

Figure 2 – Example of Parts Made with the RP Machine

2. RAPID PROTOTYPING IN A NUTSHELL

RP technology (RPT) is only about 20 years old. Development of RPT has understandably followed the development of 3-d CAD modeling often called "solid modeling". Charles Hull is credited with developing the first RP process[1]. Beaman[2] provides a detailed account of the historical underpinnings of RP. Overviews[3-10] of the RP technology are available from Beaman, Jacobs, Kochan and others. The expansion of this technology has been amazingly rapid and the publications that document this expansion have been quite prolific. Numerous publications in various journals have covered the advancing technology of RP. It is possible that one can follow the major advancements from an industrial viewpoint through the publication "Time Compression Technologies". An excellent overview is provided[11] in this publication. Another overview is provided from a more detailed research perspective in the Rapid Prototyping Journal[12]. Also, informative survey articles[13-16] can often be found in Mechanical

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Engineering which document the advantages of completely virtual prototyping[13] (the foundation of RP), applications of 3-d printing[14, 15] and a potential future of RPT being virtual reality[16]. In addition, an overview of manufacturers, which includes some brief product information as well as contact information, had been compiled by Orfe[17] and is given in the appendix.

3. PROTOTYPING AND THE DESIGN PROCESS

There are numerous ways in which to capture the essence of the design process[18, 19]; each having its own advantages and disadvantages. No matter which format is chosen to represent the design process, there will be a stage where the initial suite of design tools or methods lead to a first cut at embodiment of the product. It is at this stage that CAD models and physical prototypes are normally implemented.

According to Otto and Wood[18], some of the reasons to prototype (RP or classical) include: better understanding of the customer needs, seeing if the component will achieve its function, exploring interface issues, reducing costly iterations in the design process, public relations aspects, possibility for use in design of experiments, assembly issues, manufacturing issues, brainstorming potential and communication especially to a non-technical audience. Uses of RP in particular would include all of the above, but would also have aspects associated with the quick turn-around time and relative low cost generally associated with a RP model.

4. USE OF RP AT THE US AIR FORCE ACADEMY

4.1 RPT at USAFA

The RP machine used at the USAFA is the Genisys 3-d printer from the Stratasys Corp. (figure 1). The machine is one of a number of different options (see appendix[17] for an extended list) that use thermoplastic (in this case polyester) as a build material. The material is deposited layer by layer from a small injector at just above its melting point. The material cools quickly and hardens as it is deposited. The original cost for the Genisys machine was approximately $45,000. This included set up and training from the company as well as a first year's on-site maintenance agreement. This purchase was made three years ago. The build area (and therefore maximum size of a part) is 8x8x12 inches. In order to provide some broad estimate of build cost and time, a simple illustration may be helpful. Figure 3 shows a RP of a 1-piece compliant staple remover. The size of the compliant RP-produced device is the same as a normal staple remover (about 2 inches across the long dimension). This takes approximately 45 minutes of build time to produce and uses about $5 worth of RP material. As another reference point, figure 4 shows a full scale spindle made on the Genisys machine, which took about 6 hours to produce, and used approximately $50 worth of RP material.

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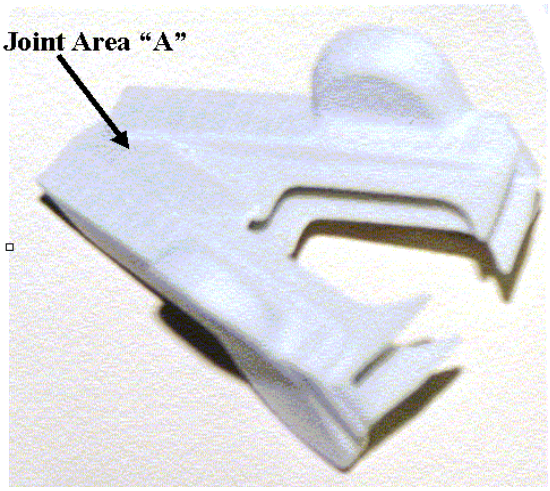

Figure 3 – 1-Piece Compliant Staple Remover Made on the RP Machine

Figure 4 – Spindle Made on the RP Machine

The actual size of the Genisys machine is approximately 4 ft wide by 3 ft high by 3 ft deep. The machine needs a network connection and a standard 120-volt power supply. The information needed to produce the RP part comes from a CAD file. In particular, the CAD model must be exported from the CAD program in the *.stl format (stereolithography files based on the original RP machines). Almost all CAD codes have this option for file export format. At USAFA we have used both AutoCAD Mechanical Desktop and AutoCAD Inventor as CAD products in the last 3 years and have had success exporting *.stl files from each. The process is virtually seamless in the new Inventor version 5. The machine runs fairly quietly (somewhat like an ink jet printer) and we have had no significant maintenance issues so far. One item to note is that completed

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assemblies cannot be printed on the RP machine. Only individual parts can be exported and then later assembled by hand.

The parts made by this RP machine have a somewhat rough surface finish due to the incremental layering construction of components. We can maintain tolerances of approximately 0.02 inches for most parts. The tolerance is significantly dependant on the type of part and even the orientation of the part as it is being built. This is due to the fact that the parts are built using the melted polyester, which solidifies on contact but maintains a certain amount of fluid viscosity for a short period of time. If parts are made where this fluid viscosity accompanied by gravity lead to reorientation of t he newly deposited material, then the tolerances may change drastically. In certain cases, this precludes the manufacture of the prototype altogether. Consider the model shown in Figure 5 of the Baja car. Students attempted to use the RP machine to manufacture the truss-like frame, but were unsuccessful. As the material was deposited, the "sag" was significant, so the decision was made to use wire for the frame and RP for the other parts.

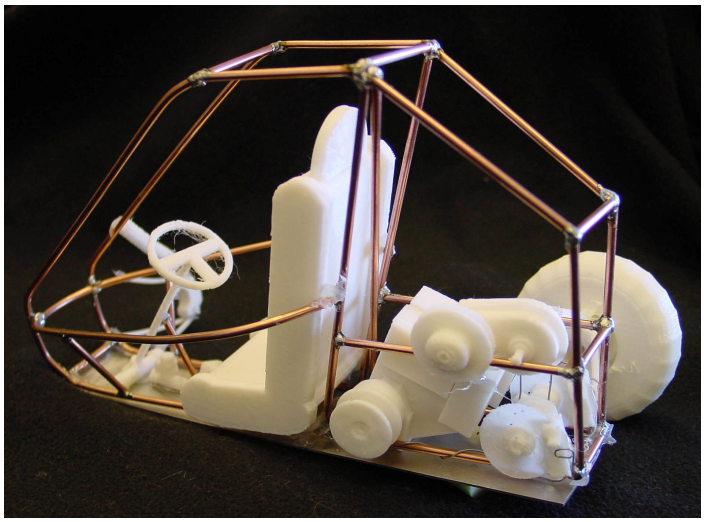

Figure 5 – Prototype of Baja Car

4.1 The USAFA classes

The two courses where we have primarily used the RPT are our sophomore-level Introduction to Design course and our Senior-level Intercollegiate Competition Design course. The Introduction to Design class exposes students to a suite of design tools including: customer needs analysis, brainstorming techniques, functional modeling, QFD, decision making tools for embodiment options, design for manufacturing, design for assembly, design of experiments and, of course, prototyping). The course includes three design projects. The first project is merely a check of cadets' abilities at prototyping and is assigned at the beginning of the semester. No formal design tools have been introduced at this point, so no structured design methodologies are expected from the students. A typical second project is the redesign of a Nerf dart gun (figure 6). A typical end-of-the-semester original design project is a mobile robot as seen in figure 7. Both the second and third projects require full manufacture and testing of the product. The

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"testing" is often accomplished in the context of a competition between the different student design teams.

Figure 6 – Nerf Dart Gun Redesign Project

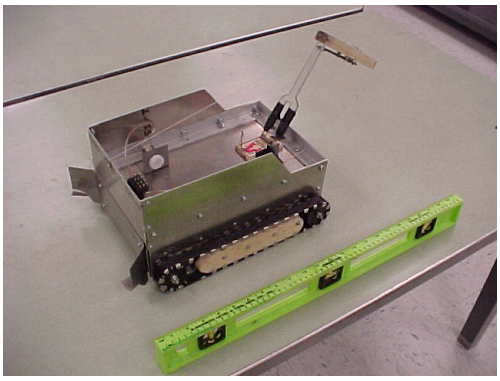

Figure 7 – Robot Original Design Project

Prototyping is encouraged in both projects and (depending on the particular instructor's preference) may be required. The prototypes made by the sophomores normally involved individual components for either the redesigned dart gun or the robot as opposed to prototyping the entire device. Students were given the option of either using the RP machine to do the prototype or using non-rapid prototyping techniques. Training was provided on the RP model making process for those cadets who expressed and interest in using the technology and pursued it. Approximately 30% of the sophomores manufactured components for their prototypes on the RP machine leaving 70% to be made using conventional means. This is commented on in greater detail in the assessment section below.

The senior-level Intercollegiate Competition Design (ICD) course normally encompasses four different projects: the ASME-sponsored Human Powered Vehicle (HPV), the SAE-sponsored Formula car, the SAE-sponsored Baja car and the SAE sponsored Heavy Lift Airplane. Each of these projects is a two-semester commitment for the team members. The first semester of the ICD course entails conceptual design and ends with a critical design review where the goal is comprehensive proof-of-concept for their proposed design. Each team is required to produce a prototype of their proposed design. The choice of prototyping technique is again left up to the students. In the case of the seniors

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almost all of the teams have chosen to use the RPT for at least a potion of their prototype. For two teams in the past semesters, the majority of the prototype has been generated using RPT. In the majority of cases, the teams have chosen to make most of the prototype using conventional means and have opted to use the RPT for only a few parts. Reasons for these choices vary and are discussed below.

4.3 Additional USE of RPT

Although the primary use of the RPT at USAFA is in the 2 classes as discussed above, the RP machine is also used in a number of other contexts. Courses including Machine Design, Introduction of Mechanics, Senior Capstone Design and Finite Elements have used the machine for various purposes. Three independent study courses have used the RP machine as a primary component of their work involving the use of finite elements to predict the behavior of compliant mechanisms. Two AFOSR-sponsored Ph.D. students have also used the RP machine to produce parts for their research in the area of compliant mechanism design.

5. ASSESSMENT

Over the three-year period that we have used the RPT, we have employed both formal and informal assessment to determine the impact of the technology. Assessment data from both students and faculty have been tabulated. Specifics are shown below.

5.1 Written Feedback from Students

Students who have had the opportunity to use the RPT were asked to provide written feedback to a survey. The survey asked seven questions shown below in Table 1.

Table 1 – Written Response Questionnaire for Prototyping

1. What was the approximate scale (1:1 or smaller) of your RP?

2. Give a brief description of what parts you prototyped and what you hoped to learn from prototyping. If you didn't use the RP Machine, please explain why you didn't.

3. What percentage of your overall prototype was done as RP (as opposed to other types of prototypes)?

4. What did you learn from your prototype that you did not learn from your CAD model?

5. How would a second, refined prototype made right before you began manufacturing been helpful?

6. What kind of parts in your final product were made in the 3D printer?

7. How much time did it take to make your prototype?

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From students' answers to these questions we have gained substantial knowledge regarding the specific use patterns for the RPT. In order to provide perspective regarding the rest of the student comments, it should be noted that only about 30% of the sophomore students chose to use the RPT for their prototypes. The remaining 70% chose to use conventional (non-RP) prototyping. We conjecture that the reason for the majority of sophomore students choosing not to use the RPT was due to the intimidation of the process; their original perception was that the time invested in producing a correct *.stl file and exporting it to the RPT would not be cost-effective compared to traditional prototyping methods. The resolution required of the prototypes for the sophomores was not very stringent. A rough prototype was adequate for the course. A completed CAD package for the parts was not due at the time the prototypes were due, so additional effort would have been required to accelerate the CAD production. Additionally, the idea of producing an exact replica of the part of interest and then not using it in the final assembly because of the polyester's low strength made students shy away from RP's use. Interestingly, the students that did use the RPT reported that the process was very easy to implement with one exception. The exception was that when using the CAD products Mechanical Desktop and Inventor version 3, the students had difficulty generating *.stl files from the CAD models. Since the release of Inventor version 4, we have not had this problem. It is reasonable to assume that part of the perceived difficulty in implementing the RP model generation process was due to the lack of mandatory training, possibly the time required to generate the CAD model, and the inability of the RPT to produce completed assemblies. All of the senior students used RPT for at least part of their prototyping. In the senior design course, comprehensive CAD was required, so that impediment was removed a priori. In addition, some formal training was provided. The training and CAD requirement most likely led to the increased use of RP by the seniors.

Students report that they almost always produced full-scale prototypes. Also, it is noteworthy that the reduced scale prototypes (like the Baja car in figure 5) were generally reported to be of less value in the design process than the full-scale prototypes. However, there are obviously cases where reduced scale prototypes have worked well.

Normally, when a team used the RPT, it was used in conjunction with other non-RP techniques. For the teams that used the RPT, there was a wide spectrum (anywhere between 10% and 90%) in the percentage of the components that were made from the RP machine. The Heavy lift airplane design team successfully used a full-scale prototype strategy that was predominately RP-based (see figure 8). They reported that the prototype uncovered substantial design issues and saved them from having to make drastic design changes later in the manufacturing phase. The Formula team also used a full-scale prototype, but used almost no RP-based parts. Instead, most of their parts were constructed using wood and foam (see figure 9).

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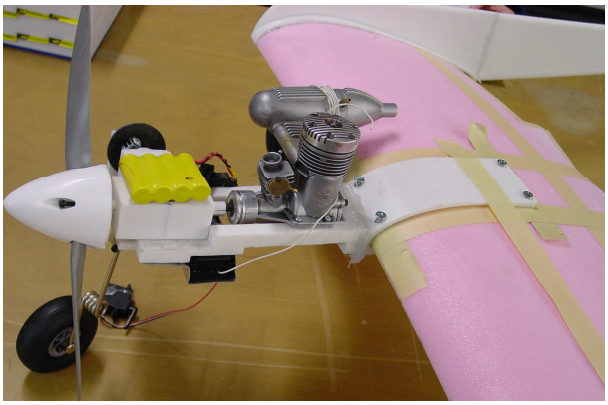

Figure 8 – Heavy Lift Airplane Prototype

Figure 9 –Mini Baja Prototype

Very few of the teams used the RP machine to fabricate parts that were used as actual production components. Two teams did use the RP-created version of a custom bracket for use in a final project. Times for production of a RP part ranged from 1 to 12 hours with an average part taking about 8 hours. This, of course is a direct function of the size and complexity of the part. Average cost of the material for the RP-based parts ranged from approximately $7 - $100. An example of a $100 part would b e the spindle is figure 4. This cost initially seems extravagant. However, in this particular case, the prototype revealed a design flaw that, if not corrected before manufacturing of the final aluminum part, would have rendered the part unusable. This mistake would have cost the team far more than $100, and resulted in significant time losses.

Probably the most interesting written feedback was to the question #4, which asked what the students learned from their prototype that they did not learn from their CAD model. All the students except one indicated that they learned things from the prototype that they did not learn from the CAD model alone. There were a large number of different responses to the question. Students indicated that they learned about constraints, strength issues, interfaces, mechanism interaction, material issues, manufacturing issues, interaction with other components and human factors issues to name just a few. In

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addition they mentioned that the prototypes aided with team communication and occasionally helped them see that an idea simply would not work. In addition, most of the seniors said that they thought that making a second, more refined prototype before they began actual manufacture of the final system would be helpful.

5.2 Numerical Feedback from Students

Numerical responses were solicited to nine statements regarding the prototyping process. Responses in the range from 0 to 4 were accepted where 0=no help, 1=minimal help2=medium help, 3=substantial help, 4=incredible help. The statements from the questionnaire are shown in table 2 below.

Table 2 – Numerical Questionnaire on Prototyping

Circle the number that best represents your answer to the following statements

0=no help 1=minimal help 2=medium help 3=substantial help 4=incredible help

a. Our prototype helped us identify or resolve interface (special interference) problems

0	1	2	3	4

b. Our prototype helped us with brainstorming

0	1	2	3	4

c. Our prototype helped us identify/resolve kinematic issues

0	1	2	3	4

d. Our prototype helped us identify/resolve human factors issues

0	1	2	3	4

e. Our prototype helped us identify/resolve manufacturing issues

0	1	2	3	4

f. Our prototype helped us identify/resolve assembly issues

0	1	2	3	4

g. Our prototype helped us identify/resolve stress or strength issues

0	1	2	3	4

h. Our prototype helped us identify/resolve displacement or stiffness issues

0	1	2	3	4

i. Our prototype helped us identify/resolve material selection issues

0	1	2	3	4

A summary of the students' replies to the nine questions is shown in Table 3. The table contains averages of all a particular category of students' responses for each question. The categories that students were grouped into are "All students" (both seniors and

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sophomores), seniors, sophomores, no-RP (those who used only classical, non-RP prototyping methods) and RP (those who used RP methods).

Table 3 – Student Response to the Prototyping Questionnaire

Prototyping helped me with…	All students	Senior	Soph	no-RP	RP
interfaces	2.5	3.0	2.3	2.6	2.0
brainstorming	2.6	4.0	2.2	2.6	1.9
kinematics	2.0	2.0	2.0	2.2	1.8
human factors	1.8	2.5	1.6	2.0	1.2
manufacturing	3.0	2.5	3.2	3.2	3.2
assembly	2.8	3.3	2.7	2.6	2.7
stress/strength	1.5	2.3	1.3	1.5	1.1
stiffness/displacement	1.6	2.0	1.5	1.6	1.3
materials	1.5	2.0	1.3	1.8	0.8
Average	**2.2**	**2.6**	**2.0**	**2.2**	**1.8**

Numerous observations can be made from the data in the table. In viewing the table, recall that 1=minimal help, 2=medium help, 3=substantial. First, note that overall, the student response from "All students" shows that students believe that prototyping was quite helpful as indicated by the average response of 2.2. In particular, areas of "interfaces", "brainstorming", "manufacturing" and "assembly" received the highest scores.

The "seniors" had a significantly higher impression of the prototyping than did the "sophomores". This is probably due in part to the fact that the seniors were driven to use the RPT while the sophomores were not. The single category where the "sophomores" rated the prototyping higher than did the "seniors" was "manufacturing". Three possible reasons for this are: 1) the sophomores used the RP parts directly in their designs when possible, 2) the sophomores were manufacturing their devices either soon after or sometimes even at the same time as they were doing their prototyping. The seniors had a significant time delay between the prototyping stage (occurs in the middle of the fall semester) and beginning manufacturing (occurs at the beginning of the spring semester) and 3) the seniors have a much greater familiarity with the manufacturing processes available to them. Note that the sophomores rank the categories of "human factors", "stress/strength", "stiffness/displacement" and "materials" quite low (all are below 2). This is likely due to the simple fact that the sophomores had not yet taken the courses to adequately deal with these topics beyond an introductory statics/strength of materials level. The RP model or traditional prototype did little to give them insight into these topics.

When comparing the "no-RP" to the "RP" categories, those who did not use RPT rated the "help" which prototyping provided higher than did those who used RPT. This result was quite surprising. When asked if how strongly they would recommend the RP use to another student, the "RP" category responded "very highly", but also indicated that specific training would be extremely helpful. It appears then that the most logical interpretation of this part of the data is that those who used the RP probably spent

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significant amounts of time learning the RP process (including CAD, file transfer and actual production of the RP part). However, once they had learned the process, they saw the benefit.

5.3 Feedback from others (profs, lab techs, industrial advisory committee)

Feedback from non-student users of the RP technology has been gathered as well. Professors teaching the design courses mentioned originally indicated that it was very difficult to navigate the process to produce RP parts. One professor in particular (John Feland) spent a tremendous amount of time developing a process for getting usable *.stl files from the earlier versions of the AutoCAD products. This paved the way for the first two years of our use of the RPT. The process of producing RP parts has become virtually seamless since the newer release of the AutoCAD products. In the last year other professors who are not teaching the design classes have begun to use the RP machine to produce learning aids for other classes. These faculty report that the process of producing parts using the RPT is quite simple. In addition, our lab technicians indicate that the machine has required little to no maintenance.

Although faculty opinion of the RP production process seems positive, an ad-hoc survey of faculty in our department revealed that the professors questioned whether the educational benefits alone justified the price for the RPT. In our case, the machine is also used for various research projects for which the RPT is an absolute necessity.

6. CONCLUSIONS AND USEFULLNESS TO OTHER INSTUTITIONS

Our work to date using RPT has led us to a variety of conclusions. First, it seems evident that prototyping (either RP or non-RP) is extremely helpful in students' design process. In particular, for the senior's Intercollegiate Design Competition teams, prototyping appears to save both time and money. This should not be surprising as the same practice is used with the same results in industry.

The integration of RP into the design curriculum into USAFA has brought forth many worthwhile lessons. RP is not all things to all people but does provide some significant pedagogical benefits. These include component visualization, interface design, assembly testing, etc. There are also some limitations on the 3D printer. The polyester material used is not strong enough for use in most student projects at USAFA. Initially the limitations of the CAD tools on the creation of *.stl files from assemblies represented a significant hurdle.

It appears from our experience to date that full-scale prototyping should be used when possible. This will, of course, limit the use of RPT in some cases. This is not to say that smaller scaled RP models should not be occasionally used. However, in most cases we have observed that students gain more insight from full-scale models.

We have also learned that requiring the use of RP technology appears to drastically increase the likelihood that students will view that technology in a positive light. It also seems apparent that students are more motivated to use the technology in situations

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where they already are required to have a CAD model and where the parts made from RP can actually be used as final parts in their design.

Finally, the big question seems to be, is the original cost of the RPT justifiable? We believe that, in our case where the RP machine serves a duel purpose as necessary equipment in a research program, then the answer is a resounding "yes". If an attempt is made to justify the cost based solely on the educational value, then the question becomes much more difficult to answer. Overall the chance to expose students to this advanced technology and highlight its use as a design tool is worth the investment. Additionally faculty have been able to use the RP device for significant research. Hopefully, the cost of this technology will decrease in a manner similar to what have occurred with computers and the question of cost justification will become mute.

7. ACKNOWLEDGEMENTS

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9. APPENDIX

Manufacturers	Systems	Stereolithography	Solid Laminated Object mftg	Selective Laser Sintering	Fused Deposition Modeling	Solider	Direct Shell Production Casting	Desktop Modeller/Prototyper	Other
3D Keltool, Valencia, CA		x							
Web: www.3dsystems.com	KerTool								
Tel: 805 257 4800, Fax: 805 257 5800									
3D Systems, Valencia, CA	SLA® stereolithography systems -								
email: moreinfo@3dsystems.com	SLA 7000/5000/3500/250	x					x		
Tel: 661 295 5600, Fax: 661 294 8406	ThermoJet solid object printer								
Cubital America Inc, Troy, MI									
Tel. 810 585 7880	Various					x			
Fax: 810 615 3722									
DPSS Lasers Inc, San Jose, CA	SLA250 Laser Upgrades								
Web: www.dpss-lasers.com	SLA 500 Laser Upgrades	x							
Tel: 408 298 7755, Fax: 408 298 7722	Solid State UV Lasers								
DTM Corporation, Austin, TX									
Web. www.dlm-corp.com	Sinterstation 2500 Plus			x					
Tel: 512 339 2922, Fax: 512 832 6753									
Light Sculpting Inc, Milwaukee WI									
Web: www.home.earthlink.net/-lightsculpting	LSI1212	x					x		Light Sculpting/Quick Layering
Tel: 414 964 5737, Fax 414 964 5737									
Liquid Control Corp, North Canton OH	Posiration Mini RPV								
Web www.liquidconlrol.com	Posiratio								
Tet 330494 1313, Fax 330494 5383	Compact Twinflow								Part Replication & Moldmaking
Minitech Machinery Corporation, Norcross, GA	Mini-Mill/2								
Web wwwminitech.com	Mini-Mill/3						x		
Tel 770 441 8525, Fax: 770 441 8526	Mini-Mill/Pro								
MSC Technologies Inc, Milwaukee, WI									
Web: www.msctech.com	LOM 2030 Plotter Replacement		x						
Tel: 414 385 8400, Fax: 414 385 8419									
Precision Optical Manufacturing, Plymouth, MI									
Web. www.pom.net	DMD Machines								Direct Metal Deposition
Tel: 734 414 7900, Fax: 734 414 7901									
Roland OGA Corporation, Irvine, CA	PNC-300								
Web: www.rolanddga.com	MODELA						x		
Tel. *9497272100/8005422307,* Fax: 9497272112	PNC-3200								
Sanders Design International, Wilton, NH									
Web www.sandersdesign.oom	Rapid Tool Maker (RTM)								Rapid Tool Maker
Tel. *6D3* 6546100, Fax. 603654 2586									
Solidscape Inc, Merrimack, NH	PatternMaster								
Tel: 603 429 9700	ModelMaker II								Ink-Jet Deposition
Fax: 603 424 1850									
Soligen Inc, Northridge, CA									
Web. www.soligen.com							x		
Tel: 818 718 1221, Fax: 818 718 0760									
Stratasys Inc, Eden Prairie, MN	FDM Quantum								
Web. www.stratasys.com	Genisys Xs 3D Printer				x		x		
Tel: 612 937 3000, Fax: 612 937 0070	FDM 2000/3000/8000								
Z Corporation, Burlington, MA	Z402 3D Printer								
Web: www.zcorp.oom	Z402C 3D Printer						x		
Tel: 781 852 5005, Fax: 781 852 5100									
Advanced Technology Systems Inc, SI Paul, MN	Stratasys machines								
Web: www.advtek.com	Genisys 3D printers				x				
Tel: 651 489 6990, Fax: 651 489 6993									
Brookfield Rapid Solutions, Hudson, NH									
Web: www.brookfield-group.com	Z-Corp						x		
Tel: 603 577 9970, Fax: 603 577 9968									
Diversfied Machinery & Sales Inc, Chesterfield, MI	SYSTEM I								
Web: www.dmsales.org	SYSTEM II								Vacuum casting equipment
Tel: 810 949 6914, Fax: 810 949 6915	SYSTEM III								
DPSS Lasers Inc, San Jose, CA	SLA250 Laser Upgrades								
Web: www.dpss-lasers.com	SLA 500 Laser Upgrades	x							
Tel 408 298 7755, Fax. 408 298 7722	Solid State UV Lasers								
InterPRO Rapid Technologies, Deep River, CT									
Web: www.interpro-rtc.com	Z Corporation Z402						x		
Tel: 860 526 5869, Fax: 860 526 8056									
Light Sculpting Inc, Milwaukee, WI									
Web: wwwhome.earthlink.net/~lightsculpting	LSI1212	x					x		light sculpture/quick layering
Tel: 414 964 5737, Fax: 414 964 5737									

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Manufacturers	Systems	Stereolithography	Solid Laminated Object mftg	Selective Laser Sintering	Fused Deposition Modeling	Solider	Direct Shell Production Casting	Desktop Modeller/Prototyper	Other
Mallett Technology, Laurel, MD									
Web: www.mallett.com	Genisys						x		
Tel: 301 725 0060, Fax: 301 725 0061									
MHO Corporation, Oakland, CA									
Tel: 510 654 6198	P-40						x		
Fax: 510 654 9157									
MSC Technologies Inc, Milwaukee, WI									
Web: www.msctech.com	LOM 2030 Plotter Replacement		x						
Tel: 414 385 8400, Fax: 414 385 8419									
PCC, Germantown, WI									
Web www.pccweb.com	GENISYS				x				
Tel: 414 251 3000, Fax: 414 251 8352									
PTE Distribution, Willowbrook, IL									
Tel: 63D 920 0597	Z CORPORATION								3D Printing
Fax: 630 920 9762									
Rand Worldwide, Mississauga, Ontario									
Web: www.rand.com	3D Systems	x					x		
Tel: 905 625 2000, Fax: 905 625 3378									
Rapid Design Technologies, Burnsville, MN									
Web www.goactua.com	Actua 2100						x		
Tel: 612 882 4660, Fax: 612 882 4662									
Shared Replicators Inc, Tulsa, OK									
Web: www sharedreplicators.com	SLA7000	x							
Tel: 918 592 0083, Fax: 918 587 7660									
SIBCO Inc, Ferndale, MI									
Web: www.sibcoinc.com	Used RP systems and upgrades	x	x	x	x		x		
Tel: 248 582 0036, Fax: 248 582 0039									
Software Marketing Consultants Inc, Blue Bell, PA	Genisys Xs								
Web. www.smcsolutions.com	Z Corp						x		
Tel: 888 762 8324, Fax: 610 260 9992									
Source Graphics, Anaheim, CA									
Web: www.sourcegraphics.com	Stratasys				x				
Tel: 800 791 9042, Fax: 714 939 0525									
TECH Inc, Perkins, OK									
Web: www.techok.com	Stratasys						x		
Tel: 405 547 8824, Fax: 405 547 8340									
Z Corporation, Burlington, MA	Z402 3D Printer								
Web: www.zcorp.com	Z402C 3D Printer						x		
Tel: 781 852 5005, Fax: 781 852 5100									
Zimmerman Products, Laguna Niguel, CA									
Tel: 949 363 8471	Zimmerman/Pauser								Layer milling process (LMP)
Fax: 405 547 8340									

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