AC 2009-2230: DESIGN AND CONSTRUCTION OF A RAPID PROTOTYPING MACHINE: A BREAKDOWN OF THE MACHINE SUBSYSTEMS USED TO LEARN MULTIDISCIPLINARY ENGINEERING SKILLS

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Design and Construction of a Rapid Prototyping Machine: A Breakdown of the Machine Sub-Systems Used to Learn Multi-Disciplinary Engineering Skills

Abstract

Described by local professors and students as a "semester project on steroids", students at the Oregon Institute of Technology set the lofty goal of designing and constructing a Rapid Prototyping (RP) machine based on an international community of "Rep-Rappers" (Replicating RP Machines) that was started at the University of Bathe, England [1]. The idea is based on building machines that can reproduce almost all of the components to make copies of themselves using the RP process, and through collaboration with other groups, implement improvements to the previous generation of machines. By looking at the machine in terms of subsystems, multiple engineering strategies and tools were employed to complete the project. The students also had to consult with experts from other departments, local industry and the internet to gather information and resolve issues that came up during the six month period. The interest and excitement expressed by other students and the impressive display of skills demonstrated by the participants has created a buzz around the college, especially considering that a commercial (RP) machine was recently purchased for more than $24K. Challenging problems were faced by the team, including software bugs, parts that required CNC machining and electronics / software integration. As a result of the work done, the group has been approached about making machines for local high schools and participating in international collaboration projects. The machine is currently being enhanced to incorporate an improved electronics package and a G code based programming capability that will provide better reliability and control of the system.

Introduction

The Oregon Institute of Technology (OIT) has a reputation of graduating engineers that are strong in applying the theory learned in the classroom through hands-on design/build projects. During the 2008 school year, sophomore students Stanley Ames and Noah Anderson expressed an interest in designing and building an inexpensive Rapid Prototyping (RP) machine from scratch by using a combination of components and electronics ordered from the internet, a shareware software available through the RepRap foundation and materials that were scavenged, donated or discounted by other departments and local suppliers. Taking a systems approach, the machine was broken down into mechanical, electrical and software sub-systems. This allowed the team to acquire all of the necessary resources and, by using university laboratory facilities (including test equipment, machine tools, welders and electronics equipment) build and troubleshoot their design.

Many university students do not have the opportunity to participate in such involved projects as building a rapid prototyping machine because of limited resources and lack of equipment. Fortunately, OIT maintains a very complete industrial fabrication facility. The machine shop has lathes, mills, CNC (computer numerically controlled) machines, and about every tool that is needed to get the job done. The welding shop is one of the most state of the art shops in Oregon with machines to accomplish just about any type of welding or cutting process. Another advantage at OIT is that in larger universities, professors are busy with research and managing large classes, and may not be accessible to students and/or not have time for projects.

The teams' primary goal was to build an affordable rapid prototyping machine with the aid of the Rep Rap foundation and minimal funds supplied by the department. This machine was built to utilize modular systems that could be taken on and off in order to experiment or improve individual components. The specific name type of RP machine to be built was a Fused Deposition Modeling (FDM) machine that could be used by students at OIT and that was in the spirit of the RepRap concept. The process of creating the OIT RepRap machine included a test machine to prove that the technology works and was a feasible goal for students Ames and Anderson. It demonstrated the core technologies and taught the students some valuable lessons that would later pay big dividends, and in fact, was the foundation of a learning experience in the real-world application and management of an engineering project. Concepts taken from Project Based Learning PBL were closely followed as a guide.

The philosophy behind Project Based Learning (PBL) is that students study concepts related to and acquire skills methods by developing a specific application. The professor in charge used PBL as the basis for defining common goals and guiding the students' progress:

1) From a project perspective

- Identify the steps required to plan for and manage a project?
- Identify resources and know-how required for success?
- Identify the structure of the collaboration process?
- Identify technologies (hardware and software) needed?

2) From a teaching perspective

- What knowledge should the student possess?
- What skills will the project teach students?
- What values and ethics are the most important?
- How does the project prepare one for employment?

Background

Rapid Prototyping (RP) is a whole suite of technologies collectively referred to as "Additive freeform fabrication" which includes Selective Laser Sintering (SLS), Stereolythography (SL), Fused Deposition Modeling (FDM®), and Layered Object Manufacturing (LOM) among others. Commercial RP was created in the 70's and 80's. Fused Deposition Modeling--the specific type of process used by the RepRap and OIT RepRap Project--was developed by S. Scott Crump in 1989 and commercialized in 1991 by Stratasys Inc. who owns the trademark for FDM® [2]. FDM works by heating up a thermoplastic, ABS in the case of RepRap, and extruding it through a small orifice onto a platform. Layers are built up successively to create a 3D model. Topographical contour lines result. The recognized accuracy (as of 2001) for FDM on a Stratasys machine—arguably the best FDM machine available—is .005 inches [3].

The 3D model is stored in an electronic format after its creation with standard CAD software such as SolidWorks, Pro-E, or Catia. The industry standard for rapid prototyping files is the STL file format developed by 3D Systems, Inc. STL files represent only the surface geometry of a part using a triangle mesh without any representation of the color, texture or other common CAD model attributes. STL files come in two formats; binary and ASCII with binary being the more common due to space issues. STL files are not currently useful for multi-material object specification but there is a trend in research toward this sort of object creation, at the least in the RepRap research community.

Layered Manufacturing (LM), of which FDM is a subset, was actually used as early as 1892 by J.E. Blanther [2] in order to make contour relief maps out of wax sheets. Later, complex 3D shapes were constructed by various researchers using different materials [4][5][6]. It wasn't until 1987 when 3D Systems created the first commercial Stereolithography (SL) system, the SLA-1 [7]. This was due to the need for advanced electronic file formats and computation ability to make use of layered manufacturing.

An advancement of the RP technology is the RepRap project. The RepRap project was started by Dr Adrian Bowyer, a Senior Lecturer in mechanical engineering at the University of Bath in the United Kingdom, with a paper published on the web [8] on 2 February, 2004 about manufacturing for the masses. RepRap stands for *REP*licating *RAP*idprototyper. It purports to be a machine capable of producing most of itself—from a volume perspective. It is currently able to replicate 60% of its own parts—mostly structural elements—and the RepRap development team is currently working on printing some of the systems electric circuits in order to increase the percentage of components that it can self-replicate.

More to the point, the RepRap project was created as an open source project with the aim of making a machine that the masses can build and operate. Since the project is open source, the plans and information are freely available online and builders are encouraged to share their results so that the whole community can benefit. Indeed, some of the key advancements in the project have come from builders not initially affiliated with the project.

The development on this project has not been restricted to academics and hobbyists. Recently a firm in the UK, Unimatic Inc., that sells educational equipment has begun offering a RepRap kit for educators called Rapman so that easier builds of a RepRap system can be used as educational aids for high school and college engineering classes without the hassles and headaches of a completely unique design and build process. This idea fully utilizes the RepRap concept.

Project Description

Beginning in the winter term of 2007, the project got underway with meetings and brainstorming sessions. Figure 1 describes the tasks that made up the six month project and the time estimated to complete each phase of the work.

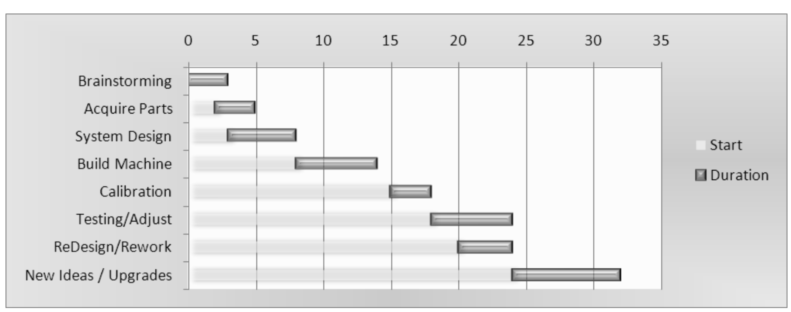

Figure 1: Gantt chart showing time line of project tasks

The OIT RP machine has three major integrated systems: mechanical electrical and software. The mechanical aspect involves the construction of the frame, motors and all moving components. Electrical hardware includes driver boards for the motors, heating elements, end switches, and a micro controller to send control signals back and forth to the computer. The software side is the most complex part to the overall system, which is an interface between the solid model on the computer and the printing of the physical part. (Refer to Table 1 on Pg. 6 for skill set)

The mechanical system starts off with a customizable frame (shown in figure 3), constructed of a rigid two foot cube made of 1/16th inch mild steel 2 inch square tube. The frame is welded together using a process called GTAW (Gas Tungsten Arc Welding). Using this process gave the frame welds a flat and small profile, yet yielded high strength. Next attached to the frame are the two X-axis guide rails, which carries the Y-axis smoothly along it (shown in figure 3). The rails were made of precision round rod mild steel and on either end of the rail where adjustable mounting plates, machined out of aluminum. Then, to move the X-axis efficiently, ball bearing carriages were mounted to two more rails which comprised of the Y-axis. The Y-axis again used ball bearing carriages to create a platform to move the extruder which was affix to it. Then, the Z-axis comprised of a MDF (medium-density fiberboard) platform supported by a metal frame and guided by two rails. UHMW (ultra high molecular weight) plastic is machine to act as a bushing for the guide rails. All three axis's X, Y, and Z were moved with ball screw assemblies powered by 200 step motors (shown in figure 4).

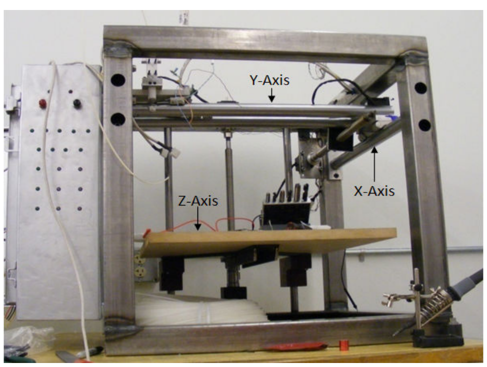

Figure 3: Frame and Axis's Layout

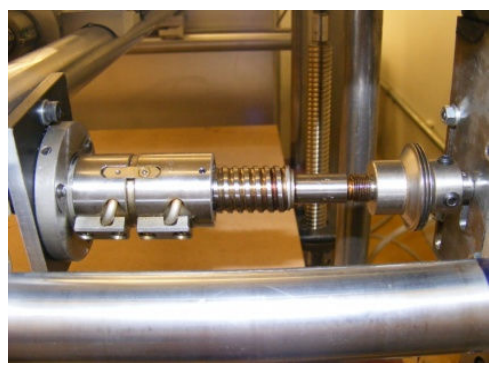
Figure 4: Ball-Screw Assembly

To finish off the mechanical system, the most important component to the machine is the extruder assembly which comprised of an extruder body, a thermal break, heater barrel, nozzle, and an auger. The extruder body was CNC milled out of aluminum which gave the part the precision and a finish that we hoped for (shown in figures 5&6). Underneath the extruder body was the thermal break made of PTFE (Polytetrafluoroethylene) or Teflon, which protected the extruder body from the heater barrel due to its thermal properties. The heater barrel was simply an aluminum threaded rod with a hole drilled through it approximately the size the feed stock. Nichrome wire is wrapped around the barrel as a heating element. The nozzle, which screws onto the heater barrel, and is an aluminum acorn nut with the appropriate extrusion tip size drilled through it, ranging from ½ mm to 1mm. The auger is a stainless steel threaded rod attached to a DC motor that drives the feed stock through the extruder assembly.

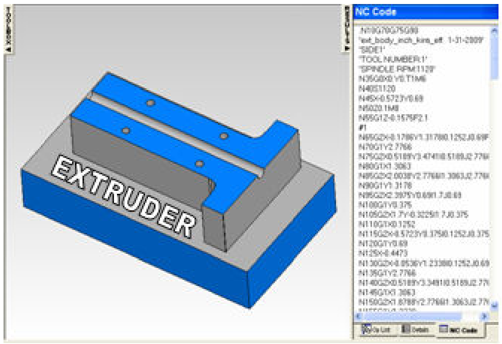

Figure 5: 3D CAM of the extruder in Feature CAM

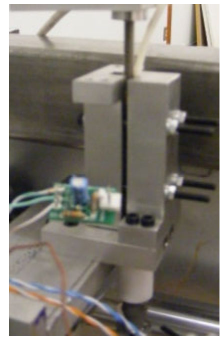

Figure 6: The Extruder

The electrical system starts off with a computer to orchestrate the Rep Rap hardware. Embedded on the side of the machine are the circuit boards that operate each electro mechanical component (shown in figure 7). The computer sends the signal to an Arduino micro controller, which then routes a signal to the correct board. First, are three stepper motor controller boards that amplify the signal sent by the computer and supplies the proper speed and direction to each motor. Second, is a pulse width modulation board, to pulse electrical current to the nichrome wire, in order to raise the temperature of the heater barrel. Once the desired temperature has been reached indicated by a thermal-resistor, slower pulses are given off to keep the temperature steady. Third, a DC motor driver board is used to control the speed and direction of the auger driver for the extruder. Fourth, the thermister board is used to input data from the thermal resistor on the extruder heater barrel back to the computer with temperature read outs. To aid in keeping track of each board and the function their performing, a bank of organized LED lights are mounted on the front the case that the electronics are housed in. Lastly, powering the machine is done with one PC power supply. For safety reasons there is one switch for the whole system which allows the operator to stop the machine in an emergency.

Finally, making this machine functional is the computer software. The software is the most important component because it turns a solid model into a usable code for the machine. After setting up system parameters for the machine, the software slices the model in to layers and generates paths based on the cross section of each layer. There are two different software programs that could be used, each was created by the RepRap Research Foundation. One software call

Figure 7: Control box containing all the electrical hardware and the computer

the Host software (shown in figure 8) generates its own code called snap protocol and has limited set up parameters. The second software called Replicator G (shown in figure 9)uses CNC M and G code and has a wide veriety of settings to optimize the machine.

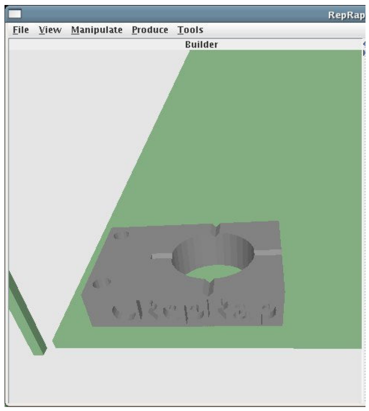

Figure 8: Host Software

Figure 9: Replicator G

Mechanical Set	**Electrical Set**	**Software/Computer Set**
Thermal Control	Motion controller boards	System Setup / Calibration
Materials Science, Plastics	Power Supplies	C++ Based Control Software
Linear Motion Systems:	Design/ Troubleshooting / Diagnostics:	Operating Systems:
Stepper Motors, Lead Screws	Electrical Circuits	Windows/Linux/
Machining / Fabrication	Wiring / Soldering / Schematics	RepRap Firmware
CAD/CAM, Solid Modeling	User Interface and Monitoring	Parameter Tables / Adjustments

Table 1: Skill sets learned and applied during rapid prototyping project

Discussion and Trouble Shooting

Frequent meetings and discussions of problems were scheduled and Dr. Culler (the responsible professor) provided some of the expertise that Ames and Anderson lacked such as CNC milling certain pieces of the extruder. During the course of the design, build, and testing of the OIT RepRap, Ames and Anderson learned many invaluable lessons that may have never been learned otherwise. The project, from this perspective, was an unqualified success.

Trouble-shooting required many hours and often led the team to change their ideas as well as some of their designs. Upon final assembly, the machine was turned on in hopes of everything working flawlessly, but unfortunately that did not happen. The stepper motors would not turn and only two of the three limit switches worked. After a little bit of research, inductance was discovered in the wiring harnesses that were routed through the steel frame to the motors. Inductance cripples electrical pulses and stepper motors can only rotate with perfect pulses. The way this was fixed was by using shielded wire instead of unshielded wire. The new wiring harnesses protected the motors from inductance and allowed the motors to work proficiently.

Limit switches are important because each time the machine goes to print something out it has to go to a home position, which is indicated by the limit switches. Without the switches the machine could not build anything because the program would be waiting for a home signal. The problem with the limit switch could not be solved, so a new piece of hardware was purchased and the switch worked fine.

Some of the test parts and related descriptions are summarized in Table 2 below. A rewarding part to create at the end of the very long process is the miniature mug. In addition, test parts provide valuable insight into the ability of the machine and how tolerances and settings/parameter settings can be modified and the resulting effect on the output and performance of the machine. Figure 10 is a snapshot taken during one of many long sessions in the lab where the work took place. Fortunately we were strongly supported by the Department Chairs (Timothy Brower and Brian Moravec) and the OIT lab technician (John Sayler).

Name	Description	Build Image
Part 1	(20mm tall) mug with gently tapering sides, it should be sufficiently watertight to raise a toast to your complete machine with.	
Part 2	(70mm tall) long-stemmed wine glass, this demonstrates the steepness of angle that the machine can print without support material.	
Part 3	A (2inch) square demonstrating an accuracy of ten thousands of an inch.	

Table 2: Test parts and descriptions

Figure 10: Team members working through assembly and wiring

Conclusions

There were many lessons learned during this project that apply to engineering education as well as to the continuation and upgrades currently being done on this machine. There is nothing that can replace enthusiasm and the willingness of the team members to consider alternative approaches to resolving problems. An additional benefit to the students was fulfilled by the need for information, either from textbooks, internet or hardware specifications, which taught them to be resourceful and creative while facing the challenges of a multi-faceted project such as the RP machine. Professors from other departments and students from both the electronics and computer science departments were intrigued and contributed greatly to the success of the project. The project brought people together into a working team, forming relationships and acquaintances that will serve our university and engineering departments well in the future. The results of the project are available on the team website which can be accessed at:

http://oitreprap.googlepages.com. The team also regularly asked questions and communicated with the international RepRap community through blogs and email. A viable next step for the project and team is to collaborate with other universities to share the experiences learned from this work and design a joint effort to follow up with a next generation cocept.

It seems that every time we reach the "end" of the project, we hear about a new piece of software or hardware that has been developed to improve the functionality and performance of the custom RP machines around the world. One of the unique features of this machine is its' open architecture and interchangeability of parts and sub-systems. The team is currently installing an upgraded set of electronics with an arduino based communication configuration as opposed to the older PIC chip setup. There is also a new software that allows the machine to be programmed using either the STL file format output from most 3D solid modeling programs or an M & G code format that is traditionally thought of when talking about Computer Numerical Control (CNC) machine tools. These changes will add versatility and robustness to the existing system. The availability of CNC control systems will allow more people to participate, afford and work on their own RP machine development projects. The team hopes to put together a kit that could be offered to younger kids at regional high/middle/technical schools. People that are interested in obtaining more information are encouraged to ask questions to the team members and share in the experience through the website and/or email correspondence.

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