A RAPID PROTOTYPING EXPERIMENT FOR UNDERGRADUATE LABORATORY COURSES

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Abstract

In this paper, the authors describe the development and implementation of a Problem-Based Learning Rapid Prototyping experiment for undergraduate laboratory courses. The laboratory is aimed at giving students a better understanding of current computer-aided product development processes and to help them improve their CAD modeling and design skills. The main body of the paper is comprised of a presentation of the corresponding laboratory manual and procedures, along with selected examples of experimental outcomes of the experiment as it was run in the spring and fall semester of 2009.

Motivation and Background

One of the authors' aims is to improve the integration of undergraduate education with ongoing faculty research and/or the utilization of existing research equipment for educational purposes. While typical problem-based learning activities are suitable for semester long courses that focus on a particular subject, it still is a challenging task to enrich traditional undergraduate laboratory courses in a similar fashion. Presently, most undergraduate laboratories focus on experiments related to the engineering fundamentals that have not changed for centuries. While many of these experiments still are an important part of a solid engineering education, there is a lack of opportunities for students to experiment with state-of-the-art technologies they will have to work with on a daily basis immediately upon graduation.

In response to this challenge, it was decided to utilize the research equipment of the Digital Fabrication Laboratory (DFL) at Georgia Tech Savannah and design a modern, computer-based experimental laboratory around it. The intention was to design a laboratory that could be leveraged in several undergraduate laboratory courses, not only in mechanical engineering but also in other engineering disciplines. The course selected for a first implementation was *ME4053 Mechanical Systems Laboratory*. It is usually taken by seniors and covers a wide array of traditional subject matter including the measurement and analysis of mechanical, acoustic, thermodynamic, fluid, and heat transfer phenomena.

As alluded to before, the nature of the new experiment to be designed for ME4053 was desired to address the integration of state-of-the-art computer-aided product development technology in the context of mechanical engineering. Hence, the topic chosen was Digital Manufacturing, and the associated experiment designed around an integration of Computer-Aided Design (CAD) with Rapid Prototyping [1,2].

In this new laboratory, students are to design or redesign mechanical parts or systems using state-of-the-art solid modeling techniques in concert with simulation software and other Computer-Aided Engineering tools. The proposed learning activities of this laboratory enhance the basic understanding of existing additive fabrication methods, 2D and 3D computer-aided modeling skills, and awareness of tolerance issues in manufacturing.

In the following sections the authors present an overview of the newly developed laboratory experiment along with a brief overview of current rapid prototyping techniques [3-1], corresponding laboratory procedures, and sample results from previous runs of the new laboratory.

A Brief Overview of Rapid Prototyping

The creation of a prototype of an artifact enables the ability for a design to be examined, specifications tested, and functionality studied while changes can still be made to the original design. There are the traditional methods of prototyping, where each prototype can be expensive to make and may require machining down if cast from a mold. Special tools may also be needed to complete the prototype. Unfortunately, traditional prototyping and assembly procedures are time demanding and costly. While new methods to expedite the manufacturing time of prototypes are being developed, so-called rapid prototyping has become a vital stage of the computer-aided product creation process.

Additive manufacturing or *layered manufacturing* [3-1] is frequently used in rapid prototyping. It uses the technique of building up layers of material instead of machining down. This method has a much faster crafting time and better detail on intricate parts of the prototype, due to the no post-manual building process. The steps required for layered manufacturing usually involve the following: First, a 3D computer model of an artifact is created with a CAD system. After the model has been created and converted into a file format that a rapid prototyping machine can read, it is broken down into small layers. The prototyping machine then prints the part, layer by layer. Depending on the techniques used, the average resolution per layer varies between 0.05mm and 0.15mm, resulting in detailed prototypes that can have intricate internal and external structures. This is a great advantage over traditional prototyping due to having everything made and put together in one machine, with various materials such as ceramics and metals, thus eliminating the machining that was once required to finish a prototype, and therefore reducing costs.

In terms of cost, the initial setup of layered manufacturing is higher than traditional methods, but the overall benefits of this new technique outweigh the cost factor. For example, any changes that may come up in the design can be made relatively quickly with a computer in the layered manufacturing, whereas the traditional piece may need additional machining to get it to the correct size or shape. Furthermore, using the traditional method, the original prototype may have to be scraped and done completely over if major changes are needed, which can be more expensive. Consequently, the main process of layered manufacturing is simpler than traditional methods, and cheaper, due to the fact that there is no need for an assembly line and extra machining and tooling.

Some of the most common rapid prototyping techniques are *stereolithography*, *selective laser sintering*, *laminated object manufacturing*, *3D printing*, and *fused deposition modeling* [3-8]. In the following sections a brief overview of typical rapid prototyping techniques is provided.

Stereolithography

Stereolithography [3, 9] is a process that uses an ultraviolet laser to cure photosensitive liquid resins. This process is highly accurate, resulting in the ability to create highly detailed parts. Acrylics, ABS–like and polypropylene–like materials can be used to create prototypes with the stereolithography process. During the build process, the ultraviolet laser traces the part's cross sectional geometry layer by layer as the base platform moves downward to create successive layers. A fluorescent light bulb is used to post cure the polymer. The advantages of stereolithography are the abilities to provide good accuracy of printing and enabling large build areas. The disadvantages are requiring the post process curing of resins and resins tend to creep over time.

Fused Deposition Modeling

Fused deposition modeling (FDM) [1, 10] uses an extruder nozzle to build a part layer by layer. The directionally controllable heated nozzle melts a plastic filament which is successively

laid upon the base plate until the part is complete as shown in Figure 1.
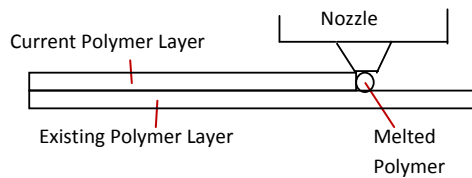

Figure 1. Layers of polymer being laid by fused deposition [1].

Small pellets can be used in place of the plastic filament. If the part contains cavities in its geometry, a filler material is placed in the cavity for support during printing. Then, the filler material dissolves when placed in a solvent. Advantages of fused deposition modeling include the ability to use a variety of thermoplastics and the ability to produce tough parts for functional use. The obtained parts can be tested and used in real world applications [8]. The disadvantages are the slow speed of the printing process and the limitations on materials used, i.e., thermoplastics are only applicable currently. In addition, the post processing procedure is critical to remove support materials that are used during the build process.

Selective Laser Sintering

Selective Laser Sintering (SLS) [6, 9] is a technique that uses high powered lasers to fuse powdered particles of plastic, ceramic, metal blends, or glass in order to form a 3-Dimensional prototype. The technique is performed by the selective material powder being laid down in a thin layer and then scanned by the laser. The laser intensity is then modulated over the layer, with high power to fuse the material particles, and the rest of the layers are treated with a lower power which allows the material to remain loose for later removal. Successive layers are made using the same process and sintered just enough to fuse the layers together. SLS can produce highly precise parts and has been successfully used for many engineering applications.

3-Dimensional Printing

3-Dimensional Printing (3DP) [5, 9] consists of a machine that works similarly to a conventional ink-jet printer. The 3D printer has multiple heads that can print parts with different colors. During the printing process, the 3DP pulls material powder from a reservoir and puts down one layer on the finished plate with a binder agent where the cross-sectional area of the part is. The advantage of the 3DP is that it can print out complex ceramic and metal parts and molds at a relative cheaper price than other rapid prototyping techniques. However, the post-processing is critical to harden the material powder once it is printed. This procedure requires more attention than other rapid techniques.

For the developed rapid prototyping laboratory in ME4053 at Georgia Tech, the manufacturing process of fused-deposition modeling and 3DP techniques are considered. In the following section, the laboratory manual and procedures developed for the new experiment are presented.

Laboratory Manual, Apparatus and Procedures

Laboratory Instrumentation

The objective of the rapid prototyping lab is for students to understand digital product development processes by designing and modeling an engineering artifact. The two main pieces of equipment for this experiment are (1) a 3D Printer, i.e., *Dimension* [1] (based on FDM technology) or a *Zcorp* [8] (based on 3DP technology), and (2) a standard PC with a 3D Solid Modeling CAD software, such as *SolidWorks*™ or Pro/Engineer™.

Experimental Procedure

Step 1: The instructor either chooses an existing functional mechanical part or designs a new one to be examined and modeled by the students. They analyze the part with regard to ease of disassembly and number of components.

An example of a functional mechanical part (a switch box) is depicted in Figure 3.

Figure 3. Functional switch box.

Step 2: Dissect the part into its simplest functional components. Try to remove any fasteners or joints since only the actual components will be modeled.

Step 3: Carefully measure the dimensions of each component or define dimensions for a new design as shown in Figure 4.

Use a 3D CAD modeling software package, such as *SolidWorks*™ or Pro/Engineer™, to create a model of the components. Verify that all relevant constraints and dimensions of the CAD model are correct. For very small parts, the model may have to be scaled. The manufacturing tolerance of the rapid prototyping equipment used is approximately 0.01 inch. Thus, students need to be aware of very intricate sections of the part or tiny parts. If this cannot be avoided, try simplifying the part to make it easier to model and print.

Step 5: After modeling is complete, save and convert the CAD model file to a `.STL` file. In *SolidWorks*™, for example, click `Save As` and change the file extension to `.STL`.

Step 6: Open the `.STL` file in the vendors' 3D printing software such as *CatalystEx*™ for *Dimension SST* and *ZPrint* for *Zcorp* 3D printer. Orient the model to minimize excessive material usage. Once the model has been adjusted for maximum efficiency, proceed with the printing process. During this process, the printing software will automatically slice the CAD model into the layered cross-sections. Then, the 3D printer will build the layers.
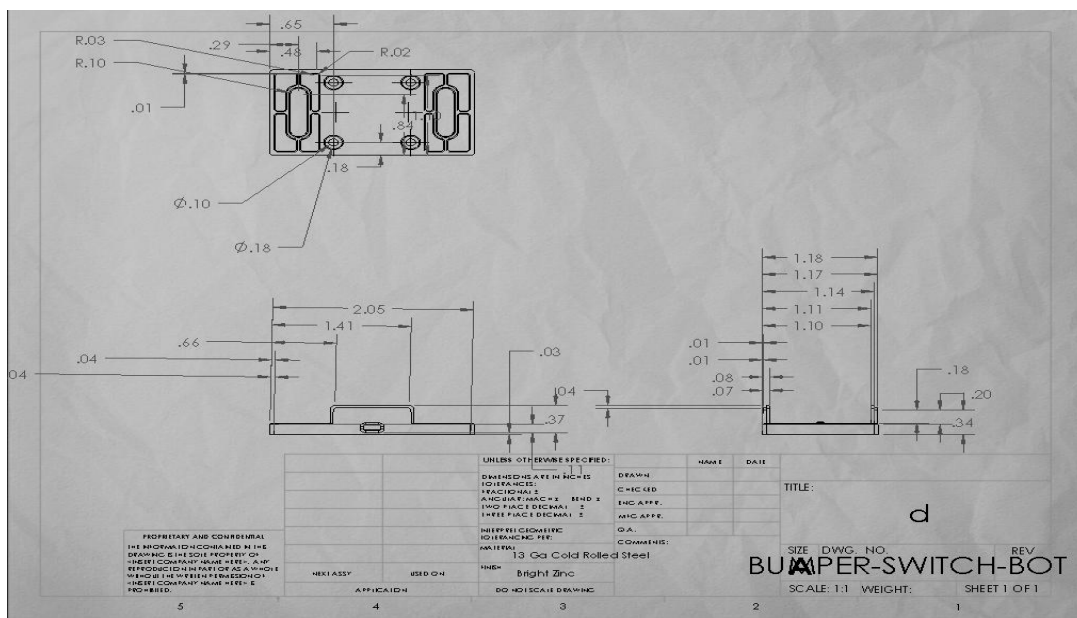

Figure 4. Dimensioning of the switch box.

Step 7: Once the printing process is complete, the model should be removed from the 3D printer. Take precaution as the printer may still be warm from the process. In the case of the FDM type printer, carefully use a scraper to remove the printed model from the tray as depicted in Figure 5.
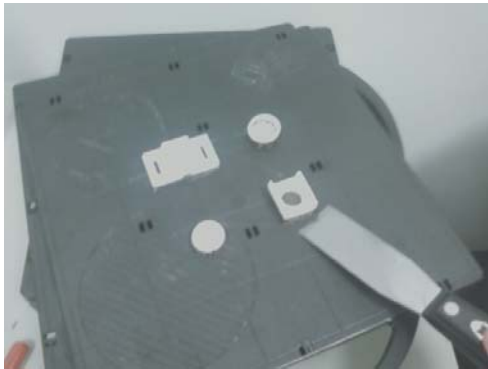

Figure 5. Scraping model parts from base.

Be sure to wear eye protection while removing the printed parts from the tray. Bits of the support material may become projectiles and cause a safety hazard. In addition, try slightly flexing the tray to help 'break' the bond between the support material and the tray. Since the post processing of the FDM technology requires more attention, it is necessary to follow steps 8-10.

Step 8: Once all parts are removed, place the pieces of the model in the solvent solution to remove all supporting material. It is sometimes helpful to place the pieces in a mesh bag as the part materials are buoyant. The bag helps to 'weigh' down the parts as shown in Figure 6.

Figure 6. Model parts in mesh.

Step 9: Turn on the solvent tank, pictured in Figure 7. Be sure to wear protective gloves whenever using the tank. The solvent in the tank will dissolve all of the support material from the part. It will heat up to its optimal temperature of 70°C.

Figure 7. solvent tank.

Step 10: Check the progress of the part after a few hours to gauge solvent time. Once all the support material has dissolved, carefully remove the mesh bag from the solvent tank. The parts will need to be rinsed with simple tap water to dilute any remaining solvent on the surfaces.

Step 11: The model is ready for final inspection. It is necessary to check any inconsistencies or misprints on the parts as shown in Figure 8.

Figure 8. Disassembled parts and prototyping results.

Once the printing processes, steps 1-11, have been completed, students are expected to submit a laboratory report including CAD drawings and printing results. They are required to address critical aspects of the rapid prototyping laboratory, i.e., potential ways of improving some steps to facilitate the printing process, potential causes of error on printed results, and suggestions as to how to overcome limitations in the future.

Sample Runs of the Laboratory Experiment

Gear Train Analysis and Design Project

A typical mechanical part to be used in this laboratory is a planetary gear train. Planetary or epicycle gear trains are found in manual pencil sharpeners, transmissions, and high torque machinery. In Figure 9 a schematic of the model of a planetary gear system is depicted. The schematic shows the dimension of each gear and an overall view of the system. A sun gear system is used to create an increase of power in a small environment. It can be found in a wide range of applications from transmissions to pencil sharpeners.
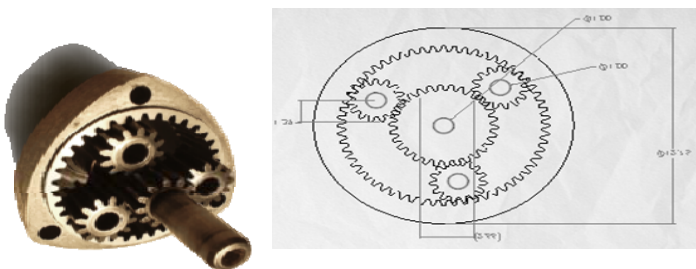

Figure 9. Gear train example (left) and CAD model (right).

In this example from a previously run laboratory, students needed to identify necessary design and model parameters based on their preliminary knowledge gained in a typical *Machine Design Course* before implementing corresponding CAD models. For instance, the number of teeth in each planet, ring, and sun gear can be calculated as

$$N_P = \frac{1}{2}N_S = \frac{1}{4}N_R \qquad (1)$$

where N_P, N_S, and N_R are the number of teeth in the planet, sun, and ring gears, respectively.

In addition, the diameter of each gear has the same ratio as the number of teeth as

$$D_P = \frac{1}{2}D_S = \frac{1}{4}D_R \qquad (2)$$

where D_P, D_S, and D_R are the number of teeth in the planet, sun, and ring gears, respectively.

If the sun gear is used as the input and the planet gears are the output, the overall gear ratio, n, can be calculated as

$$n = 1 + \frac{N_R}{N_s} \qquad (3)$$

Since the internal gear has twice as many teeth as the sun gear, the gear ratio is increased by a factor of three. The actual model was printed on a 1/2 scale in order to conserve material usages. The final prototyping result as shown in Figure 10 is fully functional.

Figure 10. 3D printing result for gear train example.

Open Topic Project

In this project, students are allowed to select a mechanical component which they will model and print. The selected model can be either an existing or a new functional mechanical part. The following examples were created by students in the fall of 2009.
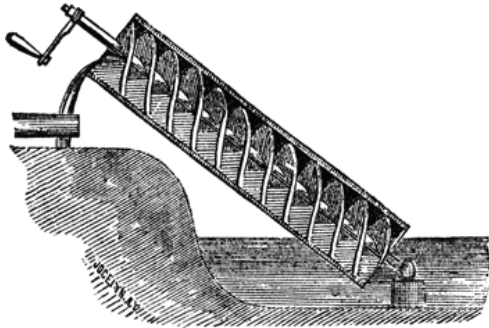

Figure 11. Archimedes screw [11].

Archimedes Screw Example (Fall 2009)

The basic design of an Archimedes Screw was developed in the 3rd century B.C. by a famous Greek mathematician Archimedes [11]. Archimedes tried to remove water from the large ship, Syracusia, by utilizing the idea of the screw as shown in Figure 11. The bottom portion of the screw is submerged in water or any other movable substance. The screw, inside of a cylinder, is turned using an attached handle. This mechanism permits the substance to move from the bottom of the cylinder to the top.

The pitch of a blade can be calculated

$$\Lambda = \frac{2\pi R_0 \lambda}{K} \qquad (4)$$

where Λ is the pitch of a blade, R_o is the radius of the screw, λ is the optimal pitch ratio, θ is the angle from horizontal that the screw is tilted, and K is the slope of the screw.

The implemented CAD model and fully and correctly functioning prototyping results are depicted in Figures 12 and 13, respectively.
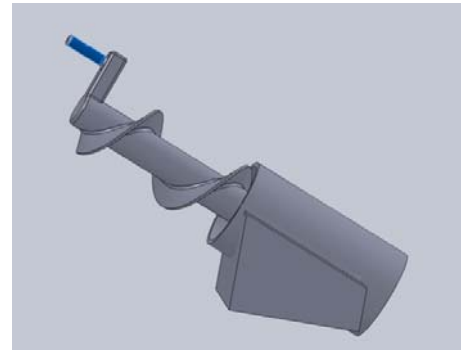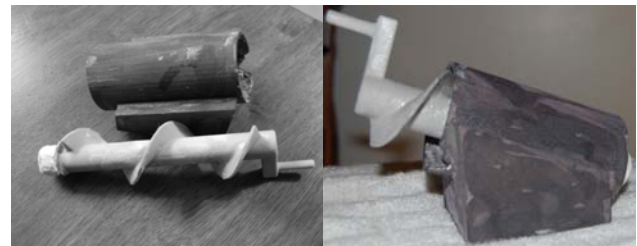

Figure 12. 3D Archimedes screw CAD model.

Figure 13. Archimedes screw prototype result.

Example 2: Tricycle (Fall 2009)

The main idea of this project is to minimize the assembly effort after manufacturing the prototype. A student selected a toy tricycle as an example and created a detailed corresponding CAD model as shown in Figure 14, while assuring the minimum assembly. The final prototyping does not require any additional assembly procedure, but all the movable parts are freely rotating and fully functional. For instance, the handles were built into the front cylinder so that the wheel would be turned when the handles were rotated. In addition, the wheels were built on axles that were a part of the structure of the tricycle body. The front wheel was also built with the pedals attached so that the tricycle could be moved by pedaling.
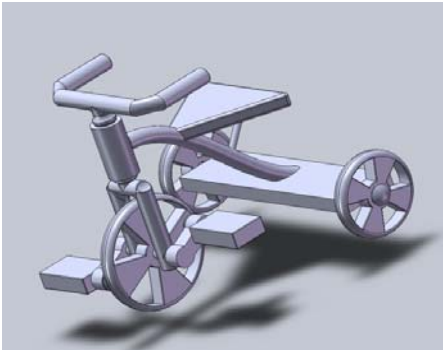
Figure 14. 3D tricycle CAD model.

The entire modeling process requires great attention to modeling errors and tolerance limit in the manufacturing equipment. The completed and fully functional model, i.e., functional steer and pedal, is shown in Figure 15.

Figure 15. Tricycle prototype (left)
and actual model (right).

Closing

In this paper, the authors presented the development and implementation of a *Rapid Prototyping* experiment for undergraduate laboratory courses that was designed as a problem-based learning experience. The experiment was first implemented for ME4053 at Georgia Tech Savannah in the spring and fall semesters of 2009. The laboratory is aimed at giving students a better understanding of current computer-aided product development processes and to help them improve their CAD modeling and design skills. The developed laboratory may be utilized in many other engineering courses as well. For example, in capstone design project courses, this new laboratory can be utilized in the final stage of the design process. Another potential usage of the presented experiment could be to make it accessible to high school or middle school students as part of activities that focus on outreach and retention. This will encourage and excite participants to pursue advanced degrees and research careers in science and technology.

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