Utilizing Rep-Rap Machines in Engineering Curriculum

Dr. Arif Sirinterlikci, Robert Morris University

Arif Sirinterlikci is the Interim Department Head of Engineering for Robert Morris University, and a University Professor. He has been involved in ASEE and SME organizations in the fields of Industrial and Manufacturing Engineering. He has conducted research in Rapid Prototyping and Reverse Engineering, Biomedical Device Design and Manufacturing, Automation and Robotics, and CAE in Manufacturing.

Miss Selin Frances Sirinterlikci, Carnegie Mellon University

Utilizing Rep-Rap Machines in Engineering Curriculum

Introduction

In this ABET accredited manufacturing engineering program, the lead author has been teaching the Rapid Prototyping and Reverse Engineering course for 8 years at Robert Morris University (RMU). The basic curriculum has been well set other than the new developments. The new developments are added to the course content on an annual basis due to the dynamic nature of both fields. In addition, the laboratories have been equipped with multiple relevant technologies including Stereolithography (SLA Viper), Fused Deposition Modeling (Dimension Elite), and 3D Printing (Prometal RXD) printers as well as Konica Minolta 910, Creaform Handyscan, and FARO Platinum Arm 3D scanning equipment.

Due to the depreciation on the laboratory equipment, maintenance, service and operational costs, the lead author has developed the concept of utilizing low cost Rep-Rap machines based on the Fused Deposition Modeling (FDM) process in the curriculum. Mendel Max 1.5 was chosen for laboratory activities. Multiple machines have been built by the students in the department as the interest towards Rep-Raps has grown, and a group was commissioned to build a machine specifically for the course. Under the guidance of a manufacturing engineering senior, two biomedical engineering undergraduates have altered the open source design available and built a Mendel Max 1.5+ machine for about \$1,000. The machine is currently employed within the course and utilizes inexpensive biodegradable PLA (polylactic acid) material for printing.

This paper will cover the basics of the Rep-Rap concept and Mendel Max 1.5 design, depict the development project and the way the machine employed in the course. The development approach teaches students about machine design including actuators, drives, extruders, their controls, and associated software tools and programming. Utilization of the machine in the course is important for understanding of the filament fabrication and materials content, Stereolithography (STL) file development and its slicing through the open source software as well as NC code generation, which is slightly different than traditional CNC programs. The Graphical User Interface (GUI) is also a good tool to demonstrate the extrusion and motion control processes. The paper will conclude with the pros and cons of such an approach and list other possible approaches.

Rep-Rap Concept

Expiring patents and availability of low cost parts and materials are allowing rapid prototyping to become as common as modern printing technology. Rep-Rap, short for replicating rapid prototypers, is the concept of designing and developing open source 3D printers to be used in replicating themselves¹. The Rep-Rap initiative was founded in 2005 by Dr. Adrian Bower from the University of Bath in the United Kingdom and is based on a variant of the FDM process called Fused Filament Fabrication (FFF)². Since its inception, the initiative has released four 3D printing machines: Darwin in 2007, Mendel in 2009, Prusa Mendel and Huxley in 2010. Each was named after biologists to emphasize the concepts of replication and evolution. The replication process has partially become realized in May of 2008 with the first completed child

machine also making parts for a grandchild. Since then the total number of partially replicated printers has been spiraling out of control. In the meantime, the first ever electronic circuit board was printed by using a Rep-Rap with the help of an interchangeable head system capable of printing both plastic and conductive solder material. In 2010, with the release of the Huxley machine, the work volume was made smaller by 30% when compared to the Mendel machines. Last few years of development included smaller companies marketing derivatives, kits, and assembled systems while lowering costs. Some of the newer designs now use open beams, Dyneema ropes instead of timing belts^{1,2}.

Mendel Max 1.5 Design and Development Process

This section covers the process of modifying and developing a Rep-Rap Mendel variant Mendel Max 1.5 shown in Figure 3. The Rep-Rap printers are based on the FFF process where a hot-end (thermoplastic extruder) mounted on a computer controlled Cartesian (XYZ) configuration deposits heated filament material on a heated bed^{1,2}. These printers are collections of steel rods and studs connected by FFF bracket designs shown in Figure 2. Mendel Max 1.5 uses a triangular prismatic shape as seen Figure 1 and 3. Stepper motors are used in driving all three axes of the printer. While X and Y axis are driven through a timing belt, Z axis is moved by two lead-screws. Just like other newer printers Mendel Max 1.5 utilizes a stepper motor for the extrusion - driving the filament, which is trapped between a splined or knurled shaft and a ball bearing^{1,2}. Gearing is also added to help aid the extrusion process.

Figure 1. Mendel Max 1.5³

Mendel's controls are handled by Arduino-based Sanguino controller and the extrusion is handled by a separate Arduino chip. Additional extruders can be added as well since each extruder can have its own chip. Two different complete Computer-Aided Manufacturing (CAM) tool sets have been developed for the Rep-Rap machines: RepRap Host written by Adrian

Bowyer and Skeinforge written by Enrique Perez. Both tools convert the 3D STL part geometry into NC machine codes, G-codes^{1,2}. A CAM tool set is comprised of three different elements used as the firmware for the microcontroller, slicer of the STL geometry, and host GUI software⁴.

Figure 2. Models of some FFF printed parts used in the assembly shown in the previous figure³

Figure 3. A grandchild Mendel Max 1.5+ machine modified and assembled at RMU

The microcontroller for the Rep-Rap machines use a firmware that controls machine functions including set up of the thermistor, estep, and other settings. The firmware can be edited with the Arduino IDE. Mendel Max developers have been recommending Marlin (GitHub) Zip downloads for firmware⁴. Slicing of the 3D STL geometry into the NC code can be handled by multiple alternatives including Kisslicer, Cura, or Slic3r, which is also recommended by the

developers⁴. Host software has a Graphics User Interface (GUI) and utilized in sending the NC (G) code to the microcontroller. Popular host software tool is Printron/Pronterface. Another alternative is Repetier, which is relatively newer but not fully proven tool, but has a nicely developed user interface⁴.

Two former RMU manufacturing engineering students, David Beddard and Charles Mura, constructed an open source wooden frame-based NC router in 2011 at the department. Then the interest of these students and others shifted to Maker Movement and especially the Rep-Rap and other open source technology. After building two Mendel Max machines and promoting them in the new National Additive Manufacturing Innovation Institute (NAMII) where the institution was in the original proposing team⁵, Charles Mura was recruited by the lead author to mentor two biomedical engineering students to build a Mendel Max 1.5+ machine. This child machine was completed by using the parent machine built by Charles Mura and is shown in Figure 3. The machine did cost slightly less than \$1,000 and it made its first successful runs late in April 2013. The Mendel Max 1.5+ machine included the following additions and CAM tools:

- Spool and controller holders were added and are not standard Mendel Max 1.5 components. They were downloaded from Thingiverse³ and printed using the parent machine.
- Rubber feet were added and the machine was leveled.
- Marlin firmware, Slic3r slicer, and Pronterface host software tools were chosen.
- New design did not include neither cooling fans nor limit switches for the homing command – G28.

In a similar effort, David Beddard and Charles Mura's senior capstone project group started working on a Digital Light Processing (DLP) machine where ultraviolet light from a projector is used to cure photosensitive resin layer by layer. After three semesters of capstone projects starting from Fall Semester 2013, the machine has been fully designed and developed and now in working condition but requires further improvement in accuracy⁶.

Utilization in the Course

The Rapid Prototyping and Reverse Engineering course has 3D printing process and associated materials content. Applications in rapid prototyping (for product development), rapid tooling, and manufacturing as well as tissue engineering and bio-printing are also included. Students have to complete a semester long development project for the AbilityOne Challenge⁷ with the goal of improving employability of handicapped people along with the course requirement of 3D printing their prototypes.

Computer-Aided Manufacturing (CAM) basics are covered via Mastercam software and NC programming through multiple tutorials. Students also go through the process of generating an STL file for the geometry to be NC machined using the Verification feature of the Mastercam. This feature of Mastercam is commonly used in 3D printing threaded polymer bars or fasteners without machining them by the lead author. Students also employ SolidWorks for designing simple pieces to be 3D printed as exercise geometry. They are also given the choice of

downloading STLs from Thingiverse³ with the hope that they will get additional hands-on time with the printers and their associated software.

Due to aging issue of commercial 3D printers in the department and high operational, maintenance and service costs, the lead author decided to use Mendel Max machines in the course and to increase their presence to 10 – 15 in the near future. Past two fall semesters, during the course of the laboratories multiple demos on Mendel Max1.5+ have been done. The students are demonstrated the operation of both the Slic3r and Pronterface. Students are also given access to the machine if they choose to use it in place of Dimension Elite.

Figure 4. An STL image of Yoda-Lite.stl⁸

The primary purpose of the program Slic3r is to convert a drawn or an uploaded .stl (Stereolithography) file (shown in Figure 4) to a G-code as a .gcode file. This file can later be opened in a text editing software such as Wordpad or Notepad as shown in the Appendix for manipulation in case of a need.

The STL image is imported into Slic3r the program by clicking File and Open, and then browsing the computer for the desired .stl file. The user can also drag and drop the .stl file into the window with the grid. Once the file is opened in Slic3r, a two-dimensional image of one of the file's layers is shown as in Figure 5. The right half of the screen is where the imported file name is displayed as well as controls such as exporting the G-code, which is the feature focused on in this study.

After the G-code is created, it must be sent to the printer so that the part can be 3D printed. One program that does this is Pronterface, properly known as Printer Interface. A G-code file can be loaded into Pronterface one of two ways. Perhaps the simplest way to load such files is through the 'Load File' button on the main toolbar. Another way to load, however, is through clicking File, then Open, then browsing for the desired .gcode file just as Slic3r could be used to find the desired .stl file.

Figure 5. An image of Yoda-Lite.stl once imported into the program Slic3r

Once a G-code is loaded, the right side of the program screen will display the following items: the path of the file, the length of imported G-code, the amount of material (filament) that the program estimates for creating the part. Other pieces of information displayed when a G-code file for a part is imported include minimum and maximum X, Y, and Z coordinates, the footprint and height calculated between the minimum and maximum X, Y, and Z coordinates, as well as the amount of layers required and the estimated time that it will take to print the part. In Figure 6, it is evident that the uploaded G-code for the Yoda should take about 2 hours, 5 minutes, and 25 seconds to print all 160 layers.

In the center of the screen in Figure 6, there is a grid where a top view of the part is displayed. This gives the printer operator a reasonable expectation of what the final product should look like. The left portion of the screen contains a group of manual controls for the machine (i.e. sending the extruder to its home in X, Y, or Z coordinates, or manually shifting it along X, Y, or Z axes by a predetermined amount. Two different parts of the machine, the heater for the hot-end (extruder) and the bed have to be set to a specific temperature, which can be done in the drop-down menus labeled “Heat” and “Bed,” respectively. The temperature currently displayed in Figure 6 for “Heat” is 185 °C and the temperature currently displayed for “Bed” is 60 °C for the PLA material used in the class. Below those toolbars, there is customizable controls for how fast the machine extrudes plastic wire after heated (the extrude option) and how fast the plastic wire is reverse back into the machine (the reverse option). The units for these controls are millimeters per minute (mm/m). Just to the right of these controls is a graph of the temperature of the hot-end/bed throughout time, which was currently offline because the Pronterface was not connected

to a printer when the image was generated. To connect a part to the printer, the user needs to click “Connect” near the top of the screen. Once the connection is made, the printing process of the part is initiated be if the temperatures are at the reference values mentioned above.

Figure 6. Yoda-Lite.gcode once imported into the Pronterface

The Mendel Max 1.5+ machine built at the institution lacks limit switches for each axis, thus use of homing buttons or G28 code will cause a crash in each axis. To prevent crashes, a home position is set near the left front corner of the bed by using G92 X0.0 Y0.0 Z0.0 while bringing the extruder head to touching position onto the bed. Then G1 X0.0 Y0.0 Z0.0 replaces the G28 code.

Conclusions and Future Work

Rep-Rap 3D printer design and development is proving to be a strong educational tool with multiple consequences. Not only great student interest is generated and maintained, but also the students are gaining and demonstrating multiple competencies (in mechatronics and NC programming) and subsequent confidence. Multiple methods were utilized by the lead author including extracurricular team approach and capstone projects during the development projects. Both methods seemed to be effective in accomplishing results with working machines and high student morale.

Utilizing Rep-Rap printers in engineering curriculum has a great advantage to it, especially in terms of costing, since very low initial investment and very low operational costs are required. There is also a great educational value in this as well, due to software and hardware being open-

sourced and accessible. Students seem to master the associated software tools and hardware rather quickly, after freely downloading them. 3D Printing is an exciting and popular subject. With the Rep-Rap approach there is less pressure but more of feeling casual informal education. But it is very involved and hands-on.

The lead author, over the years, has had evaluated the ABET Course Outcomes A, C, E, F, G, H and K from the list below:

- A. An ability to apply knowledge of mathematics, science, and engineering
- B. An ability to design and conduct experiments, as well as to analyze and interpret data
- C. An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- D. An ability to function on multi-disciplinary teams
- E. An ability to identify, formulate, and solve engineering problems
- F. An understanding of professional and ethical responsibility
- G. An ability to communicate effectively
- H. The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- I. A recognition of the need for, and an ability to engage in life-long learning
- J. A knowledge of contemporary issues, and
- K. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

With the addition of these Rep-Rap machines to the curriculum, the chance of evaluating Outcomes B and J also increases due to the availability of these machines and their costs as well as the timeliness of the subject. In terms of the Manufacturing Engineering Specific Outcomes, the following (M1 through M5) was designated by the RMU Engineering Department:

- M1. Graduates have proficiency in materials and manufacturing processes and understand the behavior and properties of materials as they are altered and influenced by processing in manufacturing.
- M2. Graduates have proficiency in process, assembly and product engineering and understand the design of products and the equipment, tooling, and environment necessary for their manufacture.
- M3. Graduates appreciate the necessity for manufacturing competitiveness and understand how to create competitive advantage through manufacturing planning, strategy and control.
- M4. Graduates are able to design manufacturing systems through the analysis, synthesis, and control of manufacturing operations using statistical and calculus based methods, simulation, and information technology.
- M5. Graduates have had laboratory experiences which enable them to measure manufacturing process variables and make technical inferences about the process.

Only M2 and M3 were employed during the assessment process. However, this portion of the assessment needs to be improved by including measures for M1 and M5 due to adding material

development components for Rep-Rap machines as well as allowing those machines to be used in actual laboratory experiments.

The main conclusion of this paper is to establish 3D printing labs with 10 – 15 Rep-Rap machines and making them available in a controlled (cost-wise) way to the students. Making these machines available to a larger audience can be managed, by requiring students to bring in their own materials and computers or SD cards. This is a similar idea to that of Christopher Williams of Virginia Tech, who is making Maker Bot machines available to his students in a form of vending where students operate them by using SD cards⁹.

Future work will be completed by assembling more similar machines and developing a low cost 3D printing laboratory that is accessible, as well as improving each machine by adding limit switches to them. Changes to the outcomes assessment will be also be carried out as defined earlier in this paper.

References

- [1] RepRap. “Welcome to RepRap.Org” http://reprap.org/wiki/Main_Page. Accessed April 10, 2013.
- [2] Wikipedia. “RepRap Project” http://en.wikipedia.org/wiki/RepRap_Project Accessed April 10, 2013.
- [3] Thingiverse. “MendelMax Thingiverse” <http://www.thingiverse.com/thing:20355> Accessed April 10, 2013.
- [4] MendelMax. “Recommended Software” <http://www.mendelmax.com/wiki/recommended-software/>. Accessed April 10, 2013.
- [5] Winning NAMII Proposal to AFRL
- [6] Sirinterlikci, A., Badger, P., Yarmea, G., Mura, C.J., Jasenak, B., Kronz, F., Tabassum, R., Swink, I., “Designing and Building Open Source Rapid Prototyping Machines”, 2013 Rapid Conference, Pittsburgh, PA.
- [7] The Institute for Empowerment. “Ability One Design Challenge” <http://www.instituteforempowerment.org/design-challenge>
- [8] Thingiverse. “Yoda - Lite” <http://www.thingiverse.com/thing:10752> Accessed January 1, 2014.
- [9] from RAPID 2013 Conference Panel - Panel Discussion: Equipping the Additive Manufacturing Workforce, Pittsburgh, PA.

Appendix – NC code generated by Slic3r for Mendelmax 1.5

; generated by Slic3r 0.9.9-dev on 2014-01-01 at 19:13:54

```
; layer_height = 0.4
; perimeters = 3
; top_solid_layers = 3
; bottom_solid_layers = 3
; fill_density = 0.4
; perimeter_speed = 30
; infill_speed = 60
; travel_speed = 130
; nozzle_diameter = 0.5
; filament_diameter = 3
; extrusion_multiplier = 1
; perimeters extrusion width = 0.53mm
; infill extrusion width = 0.53mm
; solid infill extrusion width = 0.53mm
; top infill extrusion width = 0.53mm
; first layer extrusion width = 1.00mm
```

```
G21 ; set units to millimeters
M107
M104 S200 ; set temperature
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle
M109 S200 ; wait for temperature to be reached
G90 ; use absolute coordinates
G92 E0
M82 ; use absolute distances for extrusion
G1 F1800.000 E-1.00000
G92 E0
G1 Z0.500 F7800.000
G1 X75.104 Y76.001
G1 F1800.000 E1.00000
G1 X75.634 Y75.501 F540.000 E1.04601
G1 X76.544 Y74.771 E1.11968
G1 X77.234 Y74.321 E1.17169
G1 X77.684 Y74.061 E1.20451
G1 X77.914 Y73.951 E1.22061
G1 X78.884 Y73.541 E1.28711
G1 X79.794 Y73.221 E1.34802
G1 X80.804 Y72.951 E1.41404
G1 X81.844 Y72.761 E1.48080
G1 X82.304 Y72.711 E1.51001
G1 X83.044 Y72.671 E1.55681
G1 X83.664 Y72.681 E1.59596
G1 X103.284 Y73.731 E2.83665
G1 X103.994 Y73.801 E2.88170
G1 X104.704 Y73.951 E2.92753
G1 X105.754 Y74.291 E2.99722
G1 X106.304 Y74.521 E3.03486
G1 X106.824 Y74.801 E3.07216
G1 X110.034 Y76.691 E3.30738
```