

ULTRA AFFORDABLE RAPID PROTOTYPING:
CREATION AND SETUP OF AN EXPERIMENTAL FABRICATION MACHINE

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Authorization to Submit Thesis

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Abstract

The use of rapid prototyping in engineering education is a powerful tool. It allows students to get hands on experience with emerging engineering tools as well as the design and testing process. While the cost of the machines has come down over the past several years with the introduction of 3D printers that cost several thousand dollars, the operating cost can still be a barrier for some schools, especially in the k-12 environment. To make rapid prototyping ultra-affordable new materials and methods need to be explored for use in the pursuit of creating a system that has very low cost of operation and is easy to use. This thesis focuses on the exploration of materials and methods that have low cost, primarily using post-consumer high density polyethylene in additive and subtractive manufacturing methods.

Table of Contents

Authorization to Submit Thesis	ii
Abstract	iii
Table of Contents	iv
Table of Figures	vi
Chapter 1. Introduction	1
1.1 Overview	1
1.2 Thesis Statement	2
1.3 Thesis Objectives	2
1.4 Thesis Organization	2
Chapter 2. Background	4
2.1 Motivation	4
2.2 Manufacturing methods	5
2.3 Industrial and hobby level systems	7
2.4 The RepRap Project	8
2.5 Using HDPE for prototyping	12
2.6 Common 3D Printing Problems	14
Chapter 3. Design and Manufacture of the Prototyper System	18
3.1 HDPE Shredder	19
3.2 Filament Extruder	20
3.3 The Prototyper System	22
Chapter 4. Testing and Calibration	31
4.1 HDPE shredder	31
4.2 Filament Extruder	34
4.3 Prototyper	35

4.3.1 System Configuration.....	36
4.3.2 Additive Manufacturing	38
4.3.3 Subtractive Manufacturing	46
Chapter 5. Using the System	48
5.1 How to use the shredder.....	48
5.2 Using the Filament Extruder	53
5.3 Prototyper operation.....	58
5.3.1 Basic Usage Procedures	58
5.3.2 3D Printing with the Prototyper	68
5.3.3 Subtractive manufacturing	72
Chapter 6. Designing Parts for 3D Printing.....	80
Chapter 7. Conclusions	85
Chapter 8. Future Work	89
Bibliography	92
Appendix I Prototyper Drawing Package	94
Appendix II Electrical Schematics	117
Appendix III Firmware Config.h File.....	122

Table of Figures

Figure 1. 3D printed parts are created layer by layer.	6
Figure 2. Photographs of a RepRap Mendel and Rostock. RepRap.org [5]	9
Figure 3. RAMPS, Generation 7, and Sanguilolu RepRap electronics. RepRap.org [5]	9
Figure 4. Diagram of the Generic RepRap System Configuration	10
Figure 5. J-head and an all metal hot end. RepRap.org [5]	11
Figure 6. Diagram of the material transition in a hot end.....	12
Figure 7. Curled corner of a part.	15
Figure 8. Layers separating on a print.	16
Figure 9. the proposed design and final product.....	19
Figure 10. Diagram of the extruder system.	20
Figure 11. Picture of the final system.....	22
Figure 12. The new motor mount.	24
Figure 13. The print head.....	25
Figure 14. Prototyper system build plate.	26
Figure 15. Layout of the tool head control system.	26
Figure 16. Diagram of prototyper control system.	27
Figure 17. The config.h file open in the Arduino IDE.	29
Figure 18. The Repetier Host interface.....	30
Figure 19. Pieces of milk jug ready to for shredding.	31
Figure 20. Perforated plastic sheet.....	32
Figure 21. Shredded plastic in the collection bin.	33
Figure 22. Filament extruder in a steady state setup.	34

Figure 23. Layer and perimeter print settings.....	40
Figure 24. Print speed settings.....	41
Figure 25. Skirt and brim print settings.	41
Figure 26. Filament settings for HDPE filament.	42
Figure 27. Printer size settings.....	42
Figure 28. Extruder settings for the prototyper.	43
Figure 29. Left single shell with gaps, Right double shell, both using PLA.	44
Figure 30 The interior structure of a PLA, left, and HDPE part, right.	45
Figure 31. An example of a HDPE test print.....	46
Figure 32. Print bed with a grid engraved into it.....	47
Figure 33. Cutting out the label.	49
Figure 34. Milk jug with handle cut off.....	49
Figure 35. Cutting the bottom off.....	50
Figure 36. Cutting the jug along its corner.....	50
Figure 37. Piece of milk jug being put through the shredder.	51
Figure 38. Incompletely shredded plastic sheet.....	52
Figure 39. Shredded plastic in the collection tray.	52
Figure 40. Selecting the COM port.....	54
Figure 41. Serial monitor button and temperature display.	55
Figure 42. Serial monitor displaying running temperature.....	55
Figure 43. Connecting power clip.	56
Figure 44. Guiding the filament into the hole in the baseplate.....	56
Figure 45. Reset button on the control box.....	58

Figure 46. Connect to printer button in Repetier Host.	59
Figure 47. Manual control tab.	60
Figure 48. Controls for the tool head control box.	61
Figure 49. Block next to nozzle.....	63
Figure 50. The block can now slide under the nozzle.	64
Figure 51. Nozzle height setting in Repetier Host.....	64
Figure 52. Tool inserted into the collet.....	65
Figure 53. Tool set to the height of the block.....	66
Figure 54. Tool inserted to keep spindle for turning.	66
Figure 55. Heat control in the manual control tab.	67
Figure 56. Relieving pressure so filament can be removed.....	68
Figure 57. Selecting the part to print.	69
Figure 58. Positioning the part.....	70
Figure 59. Slicing tab.....	70
Figure 60. G-code window displaying code and toolpaths.....	71
Figure 61. Print starting.	72
Figure 62. MakerCAM preference window.....	73
Figure 63. Setting units appropriately.	73
Figure 64. Selecting the desired file.	74
Figure 65. Selecting the path.	75
Figure 66. Creating the follow path operation.....	75
Figure 67. Tool path settings window.	76
Figure 68. Calculating the tool path.	76

Figure 69. Exporting toolpaths.	77
Figure 70. Saving the G-code file.....	78
Figure 71. Following the mill with a vacuum.....	79
Figure 72. Example of a complex part that can be printed without support material.....	81
Figure 73. When an overhang needs support.....	82
Figure 74. Bridging between two points.....	82
Figure 75. Coarse threaded screw, M3 bolts in plastic, and Large Printed threads.....	84
Figure 76. HDPE 3D printed test pieces, a tugboat, a cube, and an octopus.....	86

Chapter 1. Introduction

1.1 Overview

Rapid prototyping is becoming an increasingly important engineering tool. This necessitates that students learning the engineering discipline learn about it and gain experience using it in their education. It is also a useful tool in the recruitment of students into science, technology, engineering, and math (STEM) disciplines. Initiatives such as Makerbot Academy are increasingly trying to increase use of 3D printers in the classroom [1]. It's predicted that as the technology for consumer 3D printers improves 3D printing will become an important everyday part of STEM education [2]. The cost of operation of rapid prototyping machines can be a significant challenge in providing access to this technology to students early in their engineering education and even more so for students in k-12 education. An example of high operation cost would be the Stratasys Dimension rapid prototyper in the University of Idaho mechanical engineering department (\$20,000) [3]. It is a professional grade 3D printer and the materials for the machine cost around \$250 per cartridge (\$10 per cubic inch). This has led to limited use of the machine by the students as it is often seen as too expensive for frequent use. Prices have come down considerably with the introduction of consumer/hobby grade 3D printers such as the Maker Bot Replicator2 more recently purchased for the mechanical engineering department [4]. The machine costs about a tenth of what the Stratasys machine costs and its material costs between \$30 to \$50 per kilogram (about \$0.50 to \$1.00 per cubic inch). This significant reduction of cost has had the effect of increasing the frequency and scale that rapid prototyping has been used by students in class projects. If the cost of rapid prototyping could be reduced further reduced rapid prototyping could be more extensively in education. One possible way to accomplish

this would be to explore using post-consumer high density polyethylene (HDPE) as a feedstock for the rapid prototyper. HDPE can be sourced from items such as empty milk jugs, which could help bring the cost down to simply that of processing and using the HDPE to make parts.

1.2 Thesis Statement

Reducing the cost of rapid prototyping would help improve its availability for educating and recruiting students interested in STEM related fields. Post-consumer HDPE could reduce the material cost of operating a rapid prototyper if it can be used as feedstock.

1.3 Thesis Objectives

Through the construction and test of a prototype system the end to end process of taking post-consumer HDPE in its raw form and converting in to a rapid prototyped part. The system will need to convert the HDPE from a raw input such as an empty milk jug and convert it into a ready to be used medium. Then take they ready to be used HDPE and use it to fabricate a useful prototype part. There are many ways this could be accomplished. This thesis will cover the methods considered and the ones selected for implementation in the constructed system. The design of all aspects of the system documented, and the results and analysis of first use and calibration of the system will be shown and discussed.

1.4 Thesis Organization

The thesis will be composed of eight major sections. Chapter 2 will discuss the background and necessary concepts for discussing the subject. Chapter 3 will cover the design and manufacturing of the prototyper system. Chapter 4 will document testing and calibration of

the prototyping system. Chapter 5 will discuss practices recommended for using the system. Chapter 6 will cover design considerations for designing 3D printed parts. Chapter 7 will discuss the conclusions drawn from the project. Chapter 8 will go over areas that would provide good focuses for further research.

Chapter 2. Background

There are number of subjects that need to be discussed in order to explain the project. Section 2.1 will discuss the motivation and general background of the project. Section 2.2 will cover the types of manufacturing methods. Section 2.3 will explore existing manufacturing machines and how they scale in complexity from hobbyist level to industrial level machines. Section 2.4 will discuss the RepRap project and the research associated with it. Section 2.5 discusses using HDPE as a material for rapid prototyping. Section 2.6 documents some of the common challenges faced when using RepRap based 3D printers.

2.1 Motivation

Throughout a student's engineering education there are a number of tools they need to learn in order to succeed. Aside from the foundational analytical subjects such as mechanics, dynamics, thermodynamics etc., learning the engineering process is critical including designing and manufacturing prototype systems. This includes learning some of the traditional manufacturing methods as well as how to use rapid prototyping. In industry it is becoming increasingly common for engineering groups to have access to rapid prototyping systems such as 3D printers. These machines can quickly and accurately produce a model that allows the engineers to test a part for fit and function, and in some cases be used in a functional prototype. Universities have been able to acquire some of these machines for use in research and education. An example would be the Stratasys Dimension that the University of Idaho Mechanical Engineering department has [3]. While industrial machines like these are fairly reliable and produce good results, they have significant operating costs. This leads to limited use, for example for the final project in sophomore mechanical engineering design

class ME 223 student teams would get to have a part 3D printed but the team was limited to a few cubic inches in total. Lower cost 3D printers for hobby consumers have been gaining in popularity and have been making headway in education. An example would be the Makerbot Replicator more recently purchased for the Mechanical engineering department [4]. This is one the more recently released generation of consumer level 3D printer which uses raw rolls of PLA filament. Since the rolls of filament do not come in a proprietary cartridge the material cost is less than a fifth of the cost of using the Stratasys printer. With the lower operating cost, use of 3D printed parts in students' project in ME 223 and senior design has increased dramatically. In addition to acquiring the Makerbot Replicator 2 research has been conducted to look into even lower cost methods of rapid prototyping for potential use in education. An experimental system has been built for testing various approaches using post-consumer high density polyethylene as an inexpensive feedstock.

2.2 Manufacturing methods

The processes and techniques for manufacturing prototypes are many, but they can usually be classified into one of two methods or combination thereof. First being subtractive methods where material is selectively removed in order to create the part. A common example of a subtractive process would be the traditional process of having prototype part machined out of a solid block of plastic or metal. Additive methods selectively add material to create a part. One of the prominent processes is fused deposition modeling (FDM) where a thermoplastic is carefully extruded by a computer controlled extruder [3]. There are many other examples of these two manufacturing methods, this research focused on CNC machining and FDM.

FDM creates parts one layer at a time by extruding a thin line of plastic and tracing the cross section of the part. The part starts with a 3D CAD model made on a computer which then is processed to generate instructions for a printer. To create the printer instructions the processing software first slices the model into a series of cross sections. For each cross section the path the print head needs to travel in order to create the part outline and fill it in is calculated. Toolpaths for every layer are converted to printer commands which can then be sent to the printer. The printer then follows the commands precisely depositing molten plastic to create the part. This layer by layer approach can be seen in figure 1.

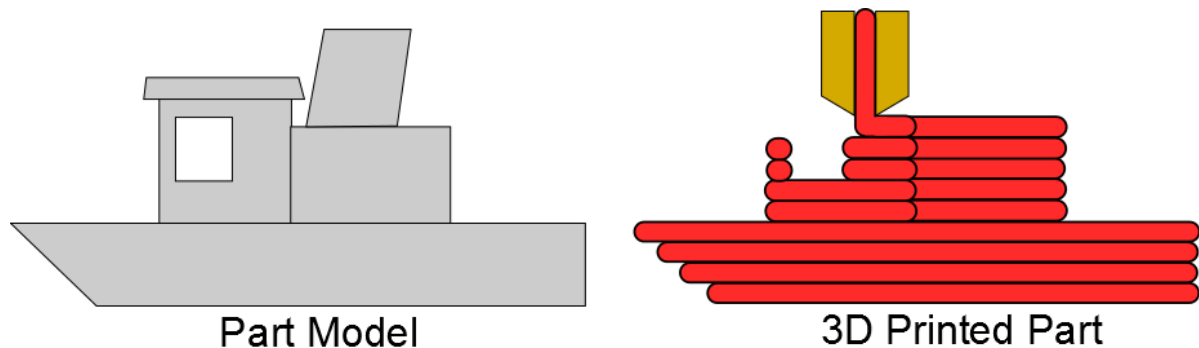


Figure 1. 3D printed parts are created layer by layer.

CNC machining starts with a piece of raw material larger than the part to be prototyped and material is selectively removed to create the part. The process begins with a completed 3D model of the part that the user then uses to create the necessary machine code. The user first imports the 3D model into a Computer Aided Manufacturing (CAM) program. Next the user must select part geometries and tools needed to create all of the toolpaths needed to make the part. Once all the toolpaths are created the program process them into commands called G-code that the CNC mill will follow to create the part. Once the code for the part is complete the user needs to set up the required tools and fixturing on the mill. Then the code

is loaded into to the machine so it can be run. The first run through the code the user takes care to make sure the code their setup works without issues such as bad offsets or code.

2.3 Industrial and hobby level systems

For both 3D printing and CNC machining there is large gap in costs and capabilities between low end machines intended for the hobbyist market and high performance industrial use machines. 3D printers in the hobbyist field range from a few hundred dollars for a rep-rap Mendel kit, which needs to be assembled and calibrated, to a few thousand dollars for a Makerbot that is ready to go out of the box [5]. Industrial 3D printers start around 20 thousand for a basic FDM and the price quickly increases to millions of dollars. For CNC machines hobby level machines start around a thousand dollars and goes up to several thousand dollars. Industrial machines start around 40 thousand and go up to millions of dollars.

As with most equipment as the price is reduced there is a compromise in some aspect of performance, whether it's speed, accuracy, rigidity, or reliability depends on what is viewed as the most important performance characteristic. For hobby level 3D printers, rigidity and reliability suffer. Hobbyist CNC machines usually sacrifice speed because platform rigidity is very important when it comes to getting good results from milling. They also favor reliability a bit more because the users often are more concerned with making parts than making the machine.

2.4 The RepRap Project

A large number of the hobbyist 3D printers are based of the technologies developed by the RepRap project. The RepRap project is an open source project aimed at making 3D printers capable of self-replication [5]. It focuses on developing the hardware and software for low cost 3D printers and making the designs and software available to the public. Due to the emphasis on low cost and open documentation making machines based off of the RepRap platform. Examples include a many 3D printers and a few other machines such as laser engravers and very light duty CNC routers/mills.

Machines built on the RepRap platform are constructed from several main components. First is the motion platform capable of moving a tool in a Cartesian coordinate system. Next there is the control electronics that power and control the movement motors and tool. There is also the tool which is usually a 3D printer extruder but is sometimes a router, laser, or other tool. And lastly there is the software that runs on the computer connected to the RepRap.

The mechanical platforms for RepRap machines are quite varied with belt and lead screw linear motion systems as well as several other methods such as delta platforms and robotic arms. The most popular systems for printers are belt driven linear systems and delta platforms. Linear systems simply have three linear rail systems, one for each axis, that either the print bed or extruder travel on. Delta platform printers have an extruder on the end of a delta robot actuator. Examples of these systems can be seen in figure 2.

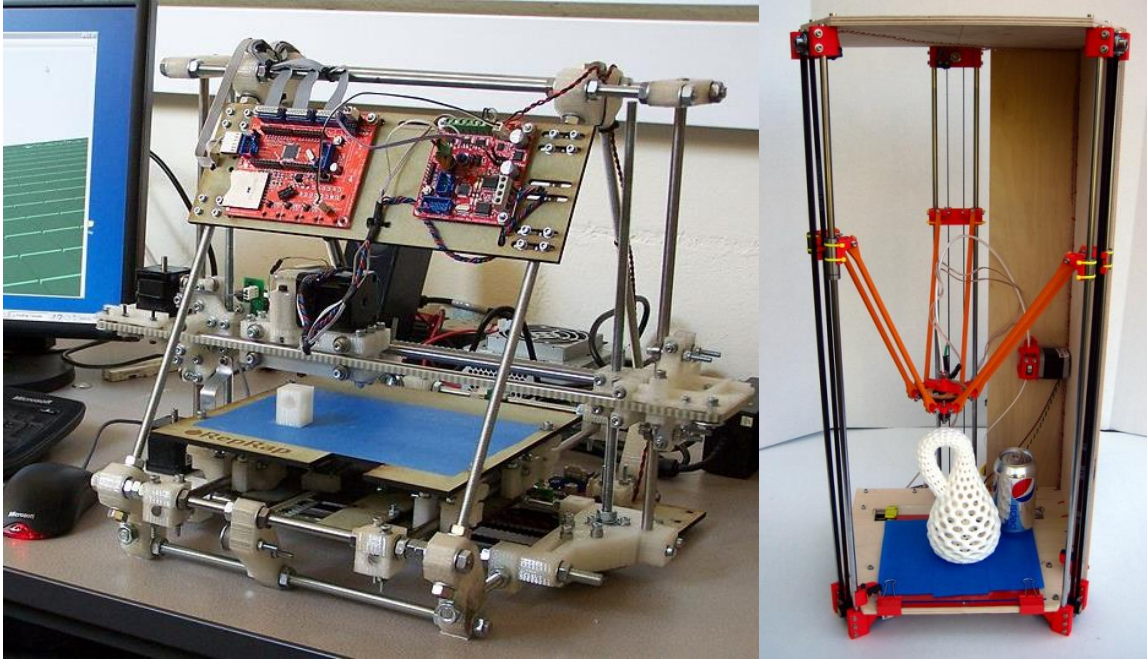


Figure 2. Photographs of a RepRap Mendel and Rostock. RepRap.org [5]

Even with the many variations of mechanical platforms they all perform the same function of XYZ translation of the print extruder in relation to the build platform. Similarly there are a number of different choices for the electrical system hardware. There is the official RepRap project board currently on generation seven, the RepRap Arduino Mega Pololu Shield (RAMPS), sanguinololu, printrboard, and others. Figure 3 shows the generation seven and RAMPS 1.4 boards.

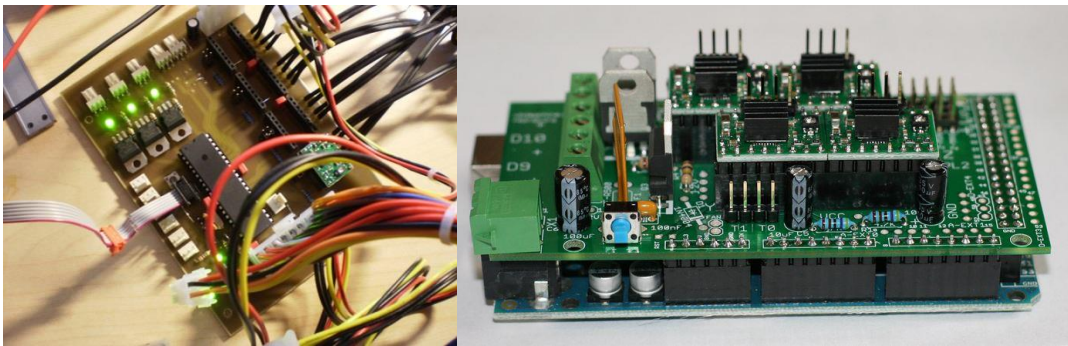


Figure 3. RAMPS, Generation 7, and Sanguinololu RepRap electronics. RepRap.org [5]

Most follow the same general architecture which is based around an Atmel Atmega microcontroller running the Arduino Mega bootloader which is connected to several stepper motor drivers, MOSFETs for driving heaters or fans, and sensors. The general layout can be seen in figure 4.

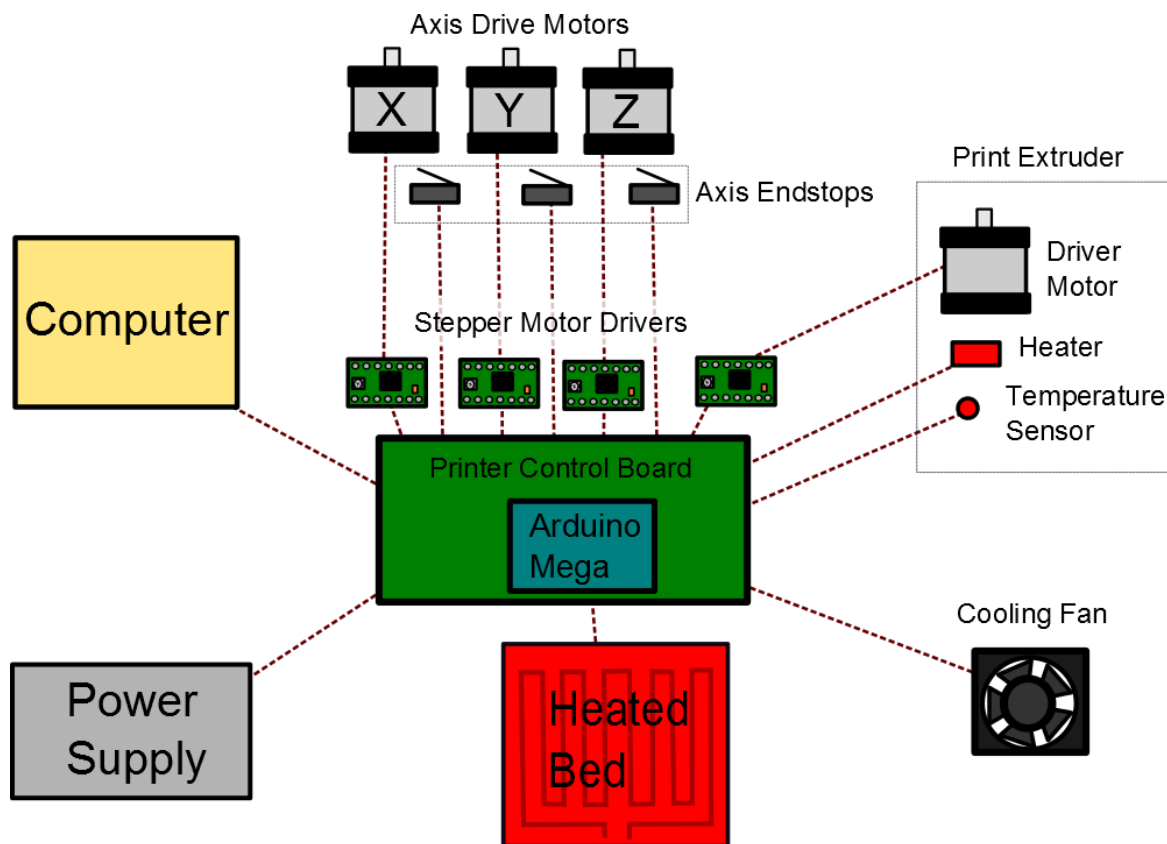


Figure 4. Diagram of the Generic RepRap System Configuration

The printhead extruder is at the heart of the 3D printer, it is what takes the plastic filament and deposits it as a fine line of molten plastic creating the part. It consists of two systems commonly referred to as the cold end and hot end [6]. The cold end is the filament drive system that precisely feeds filament into the hot end for extrusion. The hot end consists of the nozzle, heater, and barrel. The heater provides the heat to melt the filament as it flow

through the nozzle to be deposited [6]. The barrel provides a thermal break between the hot nozzle and the cold end. This is necessary for a couple reasons, first it is to help keep the filament solid before it reaches the nozzle, and second the components of the drive system can't always stand the high temperatures need to extrude plastic. Barrel designs usually take one of two approaches to create the large temperature difference necessary between the heater/nozzle and the cold end. One approach is to use a high temperature plastic such as PEEK to simply act as an insulator, this is the method used by the popular J-head style hot end [7]. The second approach is to use a heat sink to quickly dissipate the heat traveling up the barrel from the heater. Hot ends using the heat sink approach usually are made entirely of metal allowing hotter operating temperatures. Examples of these hot ends can be seen in figure 5.

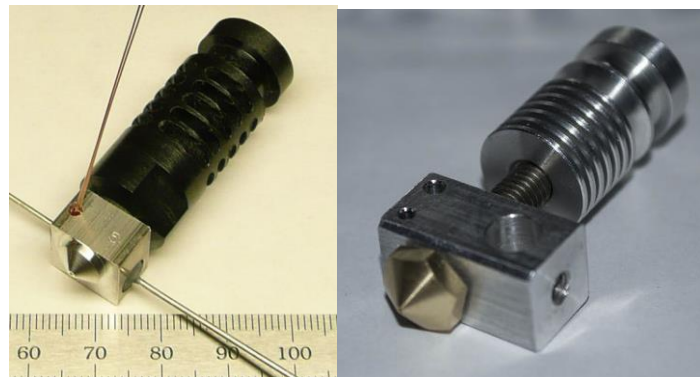


Figure 5. J-head and an all metal hot end. RepRap.org [5]

In the hot end the filament travels through temperature regions. They are the solid zone, the transition zone, and the melt zone. As the filament enters the hot end it is still cool and solid remaining in the solid zone until its temperature rises enough reach its glass transition temperature. Once it reaches this temperature it is now in the transition zone where the filament softens as it begins to transition into a liquid. In the melt zone the filament is now

fully melted and can flow through the narrow hole in the tip of the nozzle [8]. Figure 6 depicts the hot end and the temperature zones.

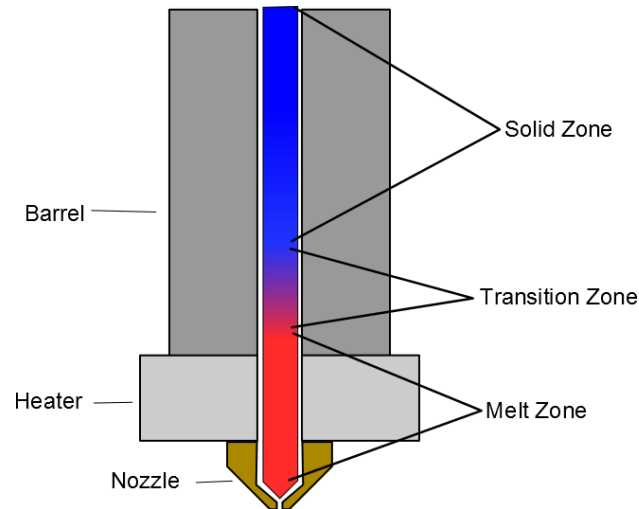


Figure 6. Diagram of the material transition in a hot end

The lengths of the transition and melt zones are very important aspects of hot end design. In the transition the friction between the wall of the barrel and filament increases dramatically and if the transition zone is too long the force need to overcome the friction becomes too great and the print head extruder will jam. Likewise if the melt zone is too long it can also cause problems [8]. If there is too much molten plastic it can flow back up the barrel causing a jam or it can flow between the threads of the nozzle and heater causing a leak.

2.5 Using HDPE for prototyping

The two most popular thermo plastics used in hobbyist level 3D printing are ABS and PLA. ABS is used because it is commercially available in filament form and is what has been historically been used in industrial level FDM printers. PLA is a newer plastic and is gaining favor for printing because it is more dimensionally stable making it easier to work with, and it is seen as more ecologically friendly because it can be biodegraded under the right

circumstances. HDPE has often been viewed as a potential rapid prototyping material because of high availability in the form of post-consumer products. Being able to recycle from sources such as plastic milk jugs would provide an abundant supply of very inexpensive prototyping feed stock and would reduce operating costs further. There are a number of reasons that HDPE is not currently in wide use in rapid prototyping. First, using post-consumer material requires secondary systems to process the raw material in the form of items such as milk jugs into a convenient to use form for rapid prototyping. Another reason is that it is one of the more difficult plastics to print with due to trouble with curling and poor adhesion [9].

One way around the problems would be instead of printing with HDPE, form it into blocks and have the part machined by a CNC mill. Blocks could be made by melting the plastic and pouring it into a mold [10]. When melting plastics it is important to have even and precise temperature application or there can be issues with overheating the material and burning the plastic causing a number of problems. One method that has been explored for a low cost solution is to cut up HDPE bottles and jugs into small pieces and melting them in a pot that is filled with oil and heated to the melting temperature. This is a simple method with decent temperature control as the temperature can be monitored with a thermometer and the oil helps evenly distribute the heat [10]. One drawback to this method is that it tends to result in small pockets of oil throughout the resulting block.

While HDPE is challenging to use in 3D printing some people in the RepRap community have managed some successful results. But before it can be used to print the raw HDPE from milk jugs must be turned into filament for printing. Work has been done in trying to create machines that allow people their own printer filament, the Lyman Extruder and the

Filabot are both notable projects. These machines currently use raw PLA or ABS pellets to create printer filament. A similar machine could be used for making HDPE filament, but this still leaves the problem of reducing milk jugs or similar HDPE sources into small somewhat consistent pieces that could be fed into a filament extruder. An additional system that can shred larger pieces of HDPE into smaller pieces is needed.

2.6 Common 3D Printing Problems

How reliable and trouble free 3D printers increases with price as is common with manufacturing equipment. Hobbyist level 3D printers have a collection of common problems related to the process and materials used. The most common of which is warping of the printed part, keeping the part adhered to the build platform, making sure the layers of the print adhere to each other, and geometric constraints such as overhangs.

How dimensionally stable a printing material is has a significant effect on whether warping will be a problem. Warping occurs when the molten plastic being deposited shrinks as it cools. When enough layers have been printed and shrink the internal stresses developed cause the part to curl [11]. Figure 7 shows an example of a curled part.

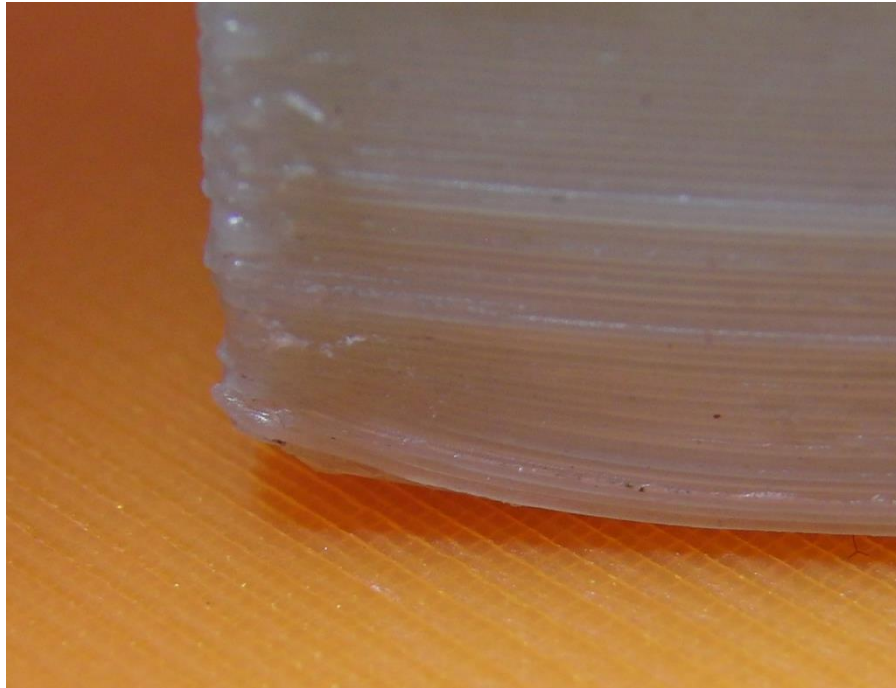


Figure 7. Curled corner of a part.

This not only results in parts that are not true to dimension it can also cause the parts to get in the way of the print extruder and collide with it. Warping occurs with ABS, PLA, and HDPE to varying degrees. PLA exhibits the least amount of warping followed by ABS with a greater but manageable degree of warping. HDPE suffers the worst warping of the three materials which is why it is not a popular choice. Warping will often cause parts to detach from the print bed mid print. This common problem has spurred a number of approaches to solve it. Two popular approaches are to use a heated print bed or to cover the print bed with a tape that the plastic will stick to. When printing with ABS a heated print bed is the primary solution, sometimes these will be covered with Kapton or polyethylene terephthalate (PET) tape. PLA is often printed without a heated print bed, usually covering the print bed with 3M blue painters tape is sufficient [11].

As each layer of plastic is deposited the molten plastic must partially melt the layer below in order for the layers to fuse together. If the plastic being deposited is not hot enough the layers will not adequately adhere and can cause problems. It can cause holes in the outer surface of a part or even cause the entire to separate destroying the part [11]. An example of an HDPE part with a layer adhesion flaw can be seen in figure 8.

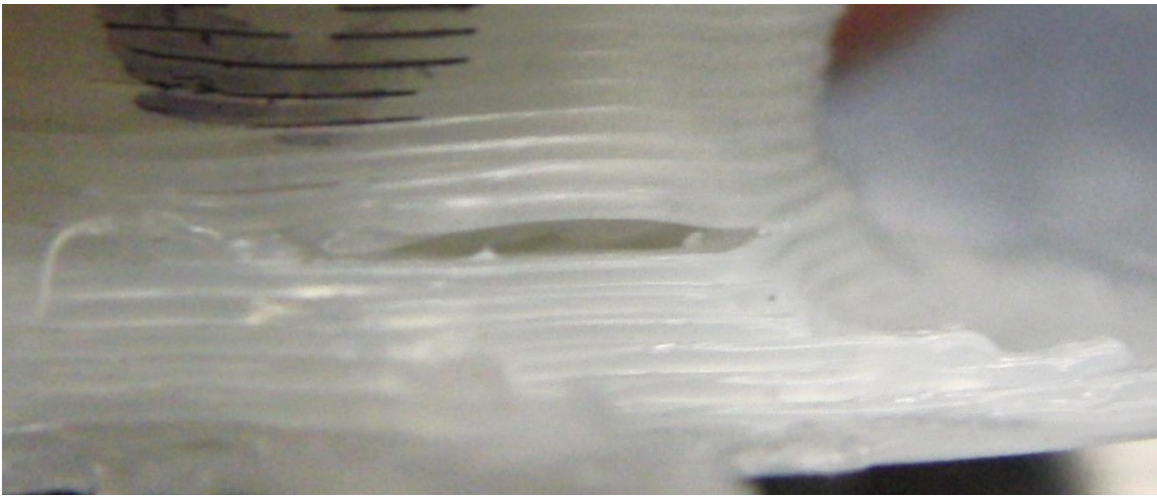


Figure 8. Layers separating on a print.

PLA has very good layer adhesion and creates parts with a strong bond between layers. ABS exhibits decent layer adhesion and on rare occasion will exhibit problems. HDPE can have issues if it is printed at too low of a temperature or if the previous layer is too cold.

Part geometry plays a very important role in how well it prints. Since each layer being printed is supported by the layer below it, parts with unsupported feature like overhangs can have issues printing. Unsupported surfaces that span between two supported points can be printed by bridging. Bridging is where the printer draws a filament between two points by extruding into the air as it traverses between the two points. If the span is too long the first few layers can sag, this leads to a loose fray of plastic filaments on the underside of the part.

Depending on the situation these problems can be solved by either printing the part with support material that has to be removed or designing the part with geometries that are optimized for 3D printing. For hobbyist level printers the support material is the same as the print material and is simply a loose pattern that is weakly attached to the part. Since it is the same material as the part it can sometimes adhere strongly to the part making it difficult to remove completely.

Chapter 3. Design and Manufacture of the Prototyper System

The system that was built needed to be able to accomplish two main tasks. First equipment was needed to process post-consumer HDPE into a ready to use format. Second there needed to be a machine that could use the HDPE to rapid prototyping of parts. Processing post-consumer HDPE sources such as milk jugs into a filament for 3D printing requires two machines. One to reduce milk jugs into small consistent pieces, and another to melt and extrude the plastic into a usable printer filament. For this work a plastic shredder and a filament extruder were constructed. Exploring various rapid prototyping methods required a machine that was flexible in its capabilities to combine additive and subtractive manufacturing. Satisfying the manufacturing flexibility needs was accomplished by building a machine capable of Cartesian movement and using a spindle and print head.

As part of the project a senior design team was given the task of helping develop some of the hardware. Their main goals were the shredder, filament extruder, and mounting the spindle and print head. Their efforts were documented in their design report which can be found on their project website [12]. This chapter is divided into 3 sections. Section 3.1 will cover the building of the shredding machine. Section 3.2 will cover the filament extrusion machine. Section 3.3 will cover the construction of the prototyping machine.

3.1 HDPE Shredder

To begin the design of the shredding machine a search was conducted for what off the shelf solutions could be found. It was determined that a robust paper shredder may serve well as the heart of the shredding machine. After passing sample pieces through a number of potential paper shredders it was found that the Ativa MD1250 12 sheet cross cut shredder performed best. In its stock configuration the paper shredder was not optimal for the task. It had a narrow opening that would not readily pass irregular pieces of plastics such as the handle of a milk jug. Also sheets of plastic passed through the machine would remain partially intact and would need to be manually sorted from the fully shredded plastic pieces. These problems were solved by repackaging the paper shredder into the form shown in figure 9.



Figure 9. the proposed design and final product

The shredder has a larger opening so it can accept irregularly shaped pieces of plastic. Small pieces of shredded plastic fall through the angled grate while the pieces that need to be run

through again fall into the easy to access bin in the front. The machine is turned on by the small red button on the front which has to be held down while running. Further details of this machine can be found in the senior design report [12].

3.2 Filament Extruder

To use the HDPE in the prototyper, a filament extruder was created to turn the small pieces from the shredder into usable filament. The design focused around using an auger system to drive the HDPE pieces through a heated barrel and out a nozzle. 1.75mm was chosen filament diameter for several reasons. 1.75 mm filament is becoming the preferred filament size for 3D printers and there was an existing supply of 1.75mm PLA from the Makerbot which could be used for testing. The system consists of a drive system, auger, power supply, hopper, extruder barrel, and heater system. The layout of the system can be seen figure 10.

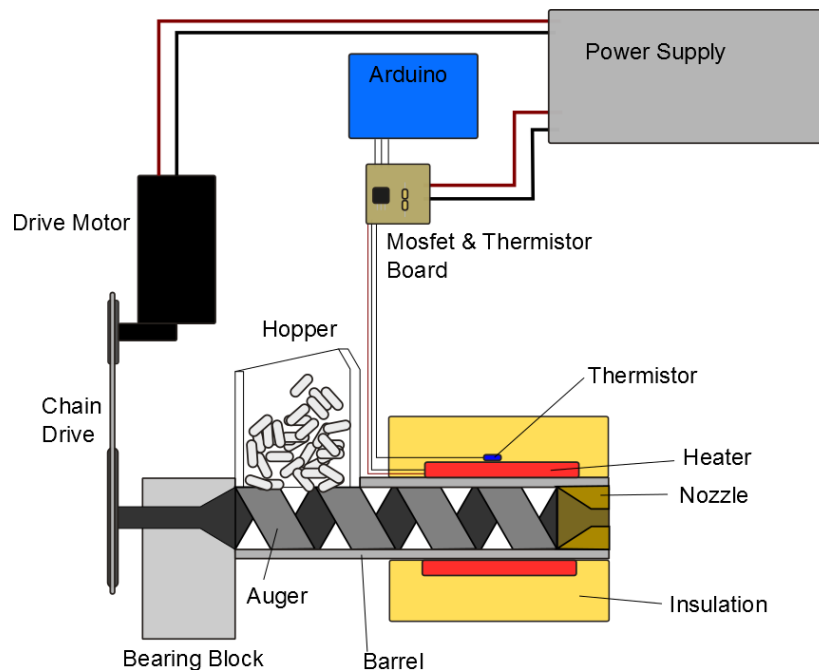


Figure 10. Diagram of the extruder system.

The drive system is powered by an automobile windshield wiper drive motor, a common choice for these types of systems due to their low cost and high torque. Speed reduction between the drive motor and auger is accomplished using sprockets and a bicycle chain. The drive sprocket was made from a 9 tooth #40 chain sprocket machined to proper thickness for a bicycle chain, and it is attached with a machined brass nut and aluminum spacer. The auger gear is a bicycle sprocket ring attached to a 3D printed plastic hub. All of this mounts to the bearing block via an adjustable plate so that the chain tension can be set appropriately. Auger alignment and thrust forces are handled by the bearings in the bearing block. A sealed ball bearing in the rear establishes alignment while a thrust washer assembly filled with white lithium grease handles the thrust force created by pushing the plastic through the extruder. The auger itself was made from $\frac{3}{4}$ " wood auger drill that was cut to length. Shredded HDPE pieces are loaded into the hopper section where the auger can feed then into the heated barrel. The hopper was made out of PLA using the Makerbot Replicator 2. The heated barrel consists of a flanged aluminum tube that has been wrapped with layers of Kapton tape for electrical isolation, nichrome wire heater elements, and thermal insulation. The nozzle threads into the end of the heated barrel with 1"-20 threads, and has a 60° conical tapered cavity to squeeze the molten plastic down to the filament size. An ATX computer power supply is used to power the system. Control of the drive motor is simply on or off. Temperature is controlled using an Arduino micro controller. This is accomplished by having the controller monitor the temperature using a thermistor that is attached to the heated barrel. Depending on the temperature, the controller either turns on or off the heating elements using a high power MOSFET.

3.3 The Prototyper System

If additive and subtractive manufacturing methods are to be explored, the prototyper needs to be flexible in its capabilities. Its primary functions can be broken down into three tasks, one linear movement in the X, Y, and Z axis, two fabrication of parts by depositing material, and three part fabrication through the removal of material. The base platform for the prototyper is a Sherline mill, chosen because it would provide a rigid platform and was already on hand. A RepRap based control box using the RAMPS 1.4 electronics configuration is used to drive the system and control the print extruder. A multi process tool head capable of switching between a small spindle for milling and a 3D printer extruder is used for fabricating parts. The final system can be seen in figure 11.

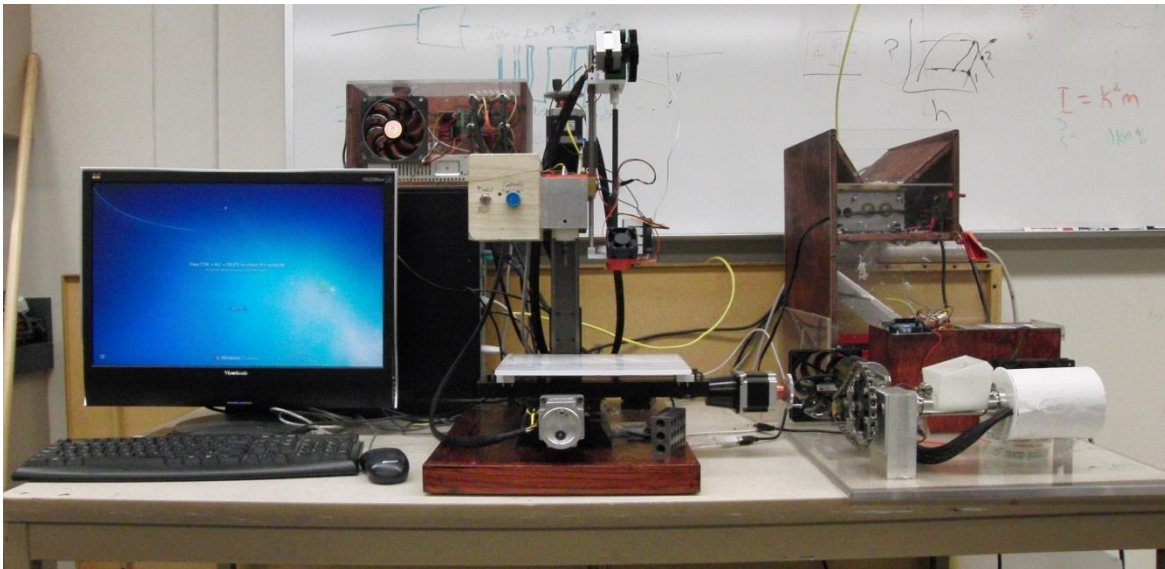


Figure 11. Picture of the final system.

There are a number of aspects that had to be considered when choosing the movement platform. 3D printers benefit most from speed which is why most employ a belt drive motion system which is fast but cannot exert much drive force and often has poor rigidity.

CNC milling on the other hand requires maximum rigidity to produce decent results. A lead screw system such as the Sherline mill sacrifices production speed for a rigid and accurate platform necessary for milling. There were several other advantageous features of the Sherline system as well. CNC conversion kits are readily available from Sherline making attaching the stepper motors to drive the axis relatively simple. The Sherline mill uses a modular spindle mounting system which makes changing the system configuration simple and fast. Removing the spindle head is done with one set screw making it possible to switch between tool heads in a couple minutes.

Converting the mill was a straight forward process. The conversion kit consisted of the motor mounts for NEMA 23 stepper motors, thrust bearings, motor shaft couplers, a new z-axis lead screw, z-axis nut, and a template block for drilling the holes needed to attach the motor mounts. Installation is accomplished by removing the axis handles, installing the new z-axis, attaching the motor mounts, and then using the mounts and coupler to attach the drive motors. If the stepper motors used are double shaft then the manual handles can be attached to the back of the motors. The NEMA 23 motors that were on hand were single shaft, so they were modified by drilling and tapping a hole on the back of the motor shaft to fit an extension for the manual handles to be attached. End stop switches were attached near the motors using 3D printed brackets. The motors and end stops were wired together into a cable that could be plugged into the printer control box.

The new tool head for the prototype consists of an aluminum mounting block to which the tools and tool controls are mounted. The print head is mounted on one side with a mechanism that moves the print head out of the way during milling operation. In the center of the mounting block is a spindle motor that was sourced from a Dremel tool. On the other

side is the tool head control system, it controls moving the print head as well as the spindle speed. The motor used for the spindle is a brushed DC motor with an 1/8" collet originally from a Dremel tool repurposed from another project. The can of the motor is bolted to a 3D printed motor mount which bolts to the mounting block. The shaft bearing is held in alignment by a 3D printed bearing guide that threads into the bottom of the mounting block. The motor mount can be seen below in figure 12.

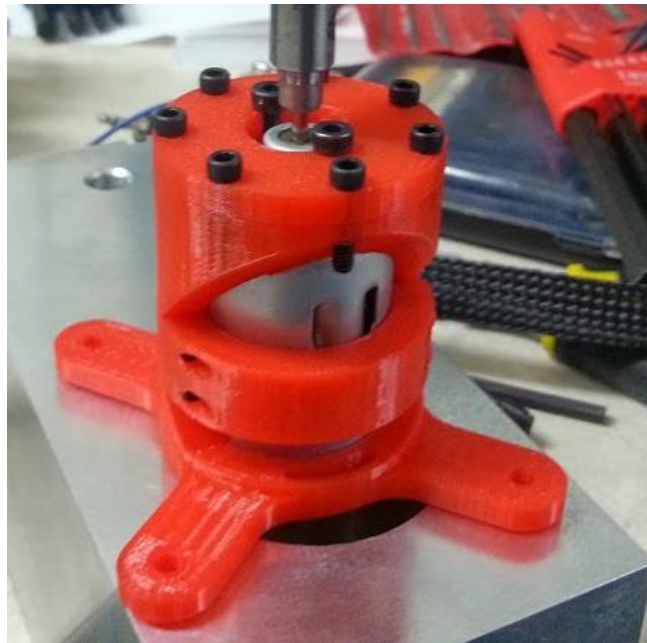


Figure 12. The new motor mount.

The print head traverses on linear rods set in a brass guide block. It is driven by a small linear actuator servo. A Greg's Wade extruder was used to drive the filament, this system is a common choice for RepRap printers. Filament is fed through tube to the hot end at the bottom of the assembly. An all metal hot end was used so that it could be used at the higher temperatures needed for HDPE. Some notable features of the hot end are it large heat sink, short barrel, and small heater block. These traits were selected to maximize the heater response and have the shortest melt transition length possible. The heat sink assembly

consisted of an aluminum mount that the barrel threaded into, and a 60 mm square computer heat sink with bolt holes machined into it. The barrel was machined from a stainless steel bolt. Stainless is a common choice for the barrel on all metal hot ends due to its low thermal conductivity for a metal. The heater block is machined out of aluminum. Heat is provided by a pair of 3W 6 Ohm resistors wired in parallel for a max output of about 48W @ 12V. Temperature is monitored by a thermistor positioned in a hole in the heater block. The barrel and nozzle use M6 threads, this allows the system to use commercially available 3D printer nozzles if desired. The current nozzle was machined to be smaller than the nozzles commercially available and uses a .4 mm hole in the tip. To quickly cool the filament being laid down the print head has a cooling duct attached to it. The cooling duct was 3D printed and is driven by a 40mm 12V fan. The print head can be seen in figure13 below.

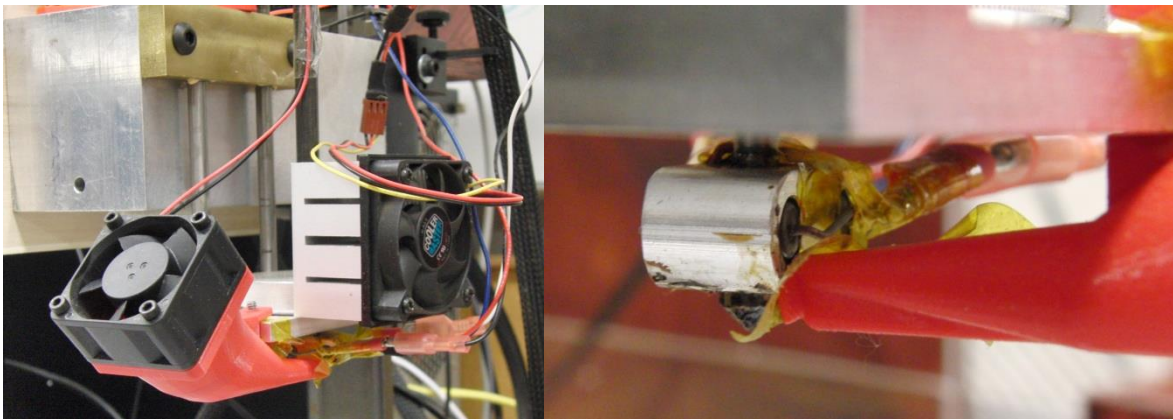


Figure 13. The print head

Printing with HDPE is difficult due to problems with adhesion to the print head, although some success has been had printing on polypropylene. The build plates for the system are made from polypropylene and can be easily interchanged. An aluminum baseplate with alignment pegs allows them to simply be pulled off or pressed on easily and supports the plates keeping them flat and level. Build plates can also be covered with clear packaging

tape that has a polypropylene backing to provide an inexpensive way to keep the print on the build plate while preserving the build plate surface. An example of the build plates used can be seen in figure 14.

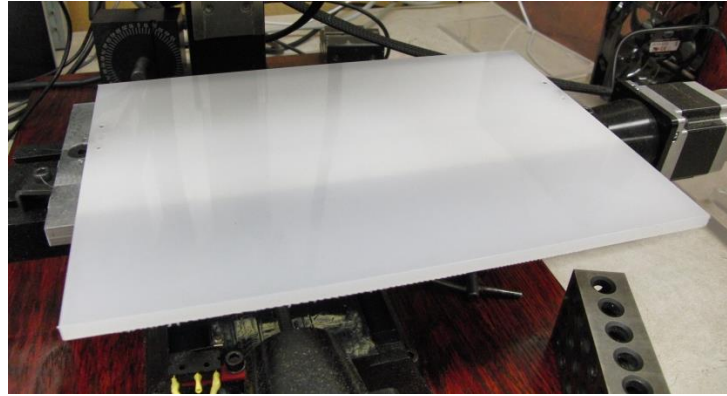


Figure 14. Prototyper system build plate.

The tool head controls are currently independent of the printer control box, so the switching between modes and spindle speed are controlled manually. Its system's main components are its power supply, Arduino Nano microcontroller, linear servo, brushed DC motor speed controller, potentiometer, and switches. The layout can be seen below in figure 15.

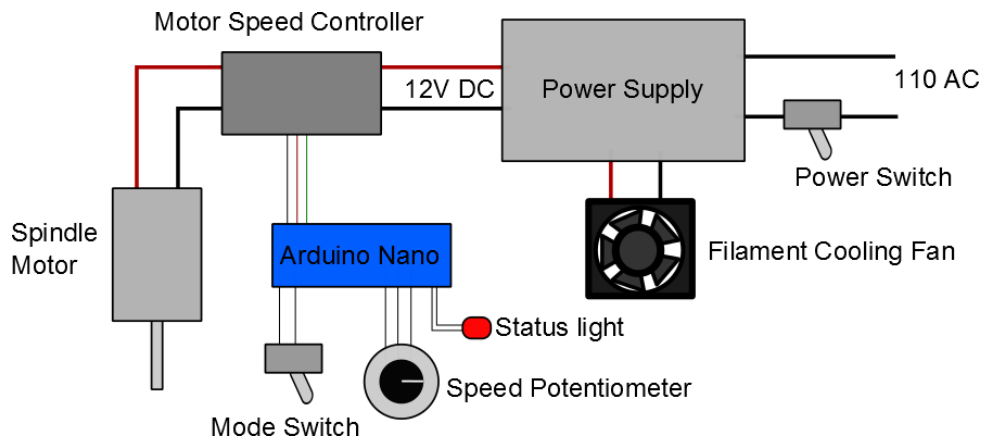


Figure 15. Layout of the tool head control system.

At its heart it has an Arduino Nano microcontroller monitoring the inputs from the mode switch and speed potentiometer, and outputting the control signals to the linear servo and speed controller. A standard three pin servo interface is used to control the linear servo and speed controller. The speed controller is a brushed DC motor electronic speed controller originally intended for RC aircraft. It was a good choice for the application for several reasons, it had sufficient current capacity for the motor, provided a simple means of motor control, provided low voltage power for Arduino and linear servo, and was inexpensive. A wiring diagram for the control box is available in appendix II. Movement and print head control are the job of the printer control box. It follows the general RepRap control electronics scheme. Its main components are the 12V 20A power supply, Arduino Mega 2560, RAMPS 1.4 controller board, and Pololu stepper motor drivers. The specific system configuration can be seen in figure 16.

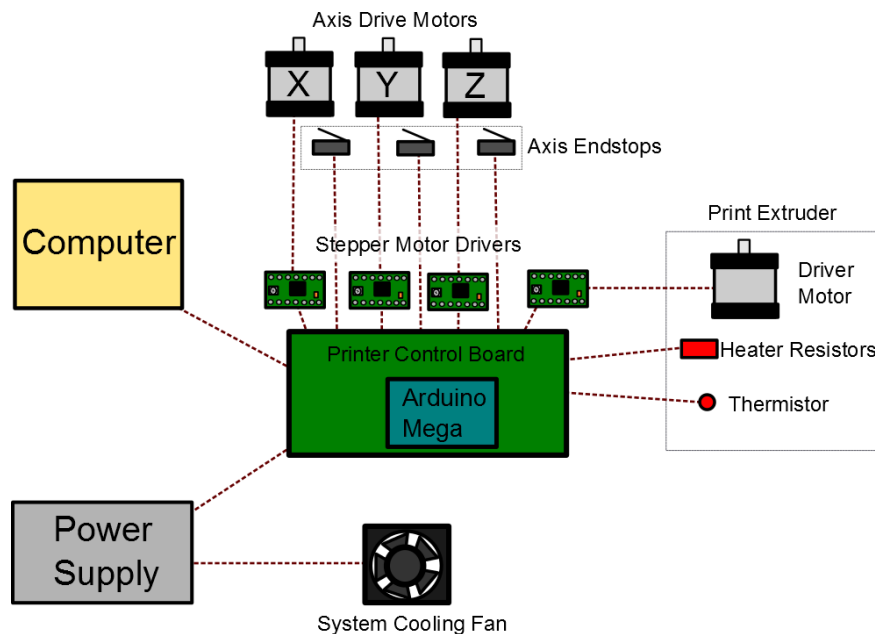


Figure 16. Diagram of prototyper control system.

This system has a few nonstandard features that should be noted. First the limit switches are only found at the maximum travel of each axis. This is because it is common for mills to have their home position where the head is all the way up and at the max limits of the X and Y axis. 3D printers more commonly have end stops on the minimum travel end of each axis or both ends. Having the Z- axis home at a height of 0 for a printer makes it easier to make sure the print head height is adjusted properly. Second the stepper drivers have been configured for $\frac{1}{2}$ step increments instead of the $\frac{1}{16}$ th step increment normally used by 3D printers. This is due the much finer resolution of movement coming from using lead screws instead of belts.

The Arduino mega in the printer control box runs a 3D printer firmware called Marlin that has been configured for the machine's specific physical configuration.[13] Marlin is currently one of the most popular of several firmwares for RepRap style 3D printers and has a good deal of documentation available. To configure the firmware it is necessary to first download the primary Arduino code for the Marlin firmware. After opening the primary program code, which should be Marlin.ino, the firmware can be configured by editing the configuration header file. The Arduino IDE with the configuration file can be seen in figure 17.

```

//=====
//-----Mechanical Settings-----
//=====

// Uncomment the following line to enable CoreXY kinematics
// #define COREXY

// coarse Endstop Settings
#define ENDSTOPPULLUPS // Comment this out (using // at the start of the line) to disable the endstop pullup resistors

#ifdef ENDSTOPPULLUPS
  // fine Enstop settings: Individual Pullups. will be ignored if ENDSTOPPULLUPS is defined
  #define ENDSTOPPULLUP_XMAX
  #define ENDSTOPPULLUP_YMAX
  #define ENDSTOPPULLUP_ZMAX
  // #define ENDSTOPPULLUP_XMIN
  // #define ENDSTOPPULLUP_YMIN
  // #define ENDSTOPPULLUP_ZMIN
#endif

#ifdef ENDSTOPPULLUPS
  #define ENDSTOPPULLUP_XMAX
  #define ENDSTOPPULLUP_YMAX
  #define ENDSTOPPULLUP_ZMAX
  // #define ENDSTOPPULLUP_XMIN
  // #define ENDSTOPPULLUP_YMIN
  // #define ENDSTOPPULLUP_ZMIN
#endif

// The pullups are needed if you directly connect a mechanical endswitch between the signal and ground pins.
const bool X_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the endstops.
const bool Y_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the endstops.
const bool Z_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the endstops.
// #define DISABLE_MAX_ENDSTOPS

```

Figure 17. The config.h file open in the Arduino IDE.

The primary things that needed to be configured are the control electronics type, thermistor type, endstop configuration, printer dimensions, steps per mm for XYZ translation, steps per mm for filament extrusion, movement max speed, homing movement speed, and max acceleration. All of the specific settings for the prototyper's configuration are available in appendix III which contains the config.h header file used.

Software is needed to process user's 3D model for printing and to send commands to the printer controller. For this project it was chosen to use Repetier Host as the primary host software. It is a widely available printer host program that allows for user control of the

prototyper and incorporates a slicing engine for processing 3D models into printer commands. Repetier Host includes two common slicing engines Skeinforge and Slic3r. For this project Slic3r was the slicing engine used. What the Repetier Host interface looks like can be seen below in figure 18.

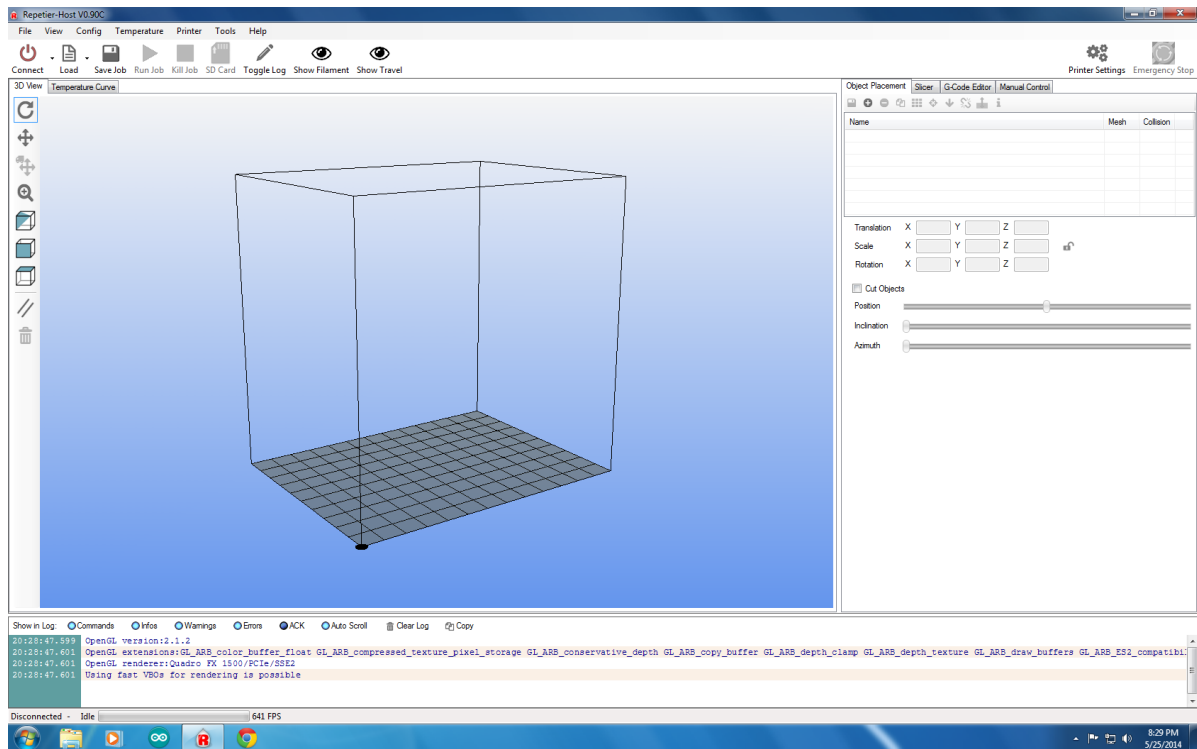


Figure 18. The Repetier Host interface.

Chapter 4. Testing and Calibration

Once the system is complete testing began. Each individual machine needed to be put through its paces to figure out the most effective operating methods. The limits of what the shredder can handle and how to get the best results needed to be tested. Filament consistency and extrusion speed of the filament extruder and what affects them needs to be documented. And lastly the capabilities and necessary configuration of the prototyper system needed to be explored and documented. 4.1 covers the testing of the shredder. 4.2 goes over the testing of the filament extruder. 4.3 discusses the prototyper including its configuration and results.

4.1 HDPE shredder

Testing the shredder was fairly straight forward. As using empty milk jugs was the primary focus testing focused on how much the milk jugs needed to cut into smaller pieces and how large/many pieces can be processed without the shredder stalling. The testing process began by cutting up a number of empty and washed milk jugs into pieces of varying sizes from small squares to the entire side of a milk jug. What the pieces look like can be seen in figure 19.



Figure 19. Pieces of milk jug ready to for shredding.

Starting with small pieces, pieces were fed into the shredder. Successively larger pieces were selected until the limits of the shredder were hit, indicated by the shredder bogging down and disabling its drive motor. It was found that large single sheet pieces passed through without much difficulty, but often required at least two passes to completely shred it into small pieces. The results of an incompletely shredded sheet can be seen in figure 20.



Figure 20. Perforated plastic sheet.

Pieces with a thickness twice that of the wall of a milk jug would overload the shredder and cause it to disable its drive motor. The most common cause of the shredder being overloaded was large irregularly shaped pieces and too many pieces at the same time. It should be noted that small irregularly shaped pieces such as the handle of a milk jug can be passed through if they are inserted individually. The sorting grate worked as intended and allowed for the fully shredded pieces to fall through into the collection drawer while keeping the large pieces out so they can be run through again. Figure 21 shows the resulting pieces in the drawer.



Figure 21. Shredded plastic in the collection bin.

Another common source of HDPE is plastic shopping bags. These were not considered as it was believed they did not contain a significant amount of plastic and it was believed they wrap around the shredder teeth and cause jams. To verify this a small piece of plastic shopping bag was fed into the shredder. As expected the piece of plastic shopping bag immediately wrapped around the shredder teeth, and it had been a large enough piece it would of caused the shredder to stall. HDPE filament made with the extruder that was not appropriately sized was also ran through the shredder to see if it can be reprocessed. Filament would often only get broken into pieces that were several inches long but still pass through the grate as it had a small cross section. Another problem filament had was that it would some time wrap around the shredder teeth and get stuck in the shredder.

4.2 Filament Extruder

The focus of testing the filament extruder was how to get filament of a consistent usable diameter. Initial testing focused on how to get the filament extruder to run reliably and to see how to get filament of consistent diameter. In order to get a consistent diameter it was thought that attempting to set the machine up to achieve steady state operation. To accomplish a steady state the machine was set up on a table so that as the filament came out of the extruder it would feed over the edge and then coil on the ground. The setup can be seen in figure 22.

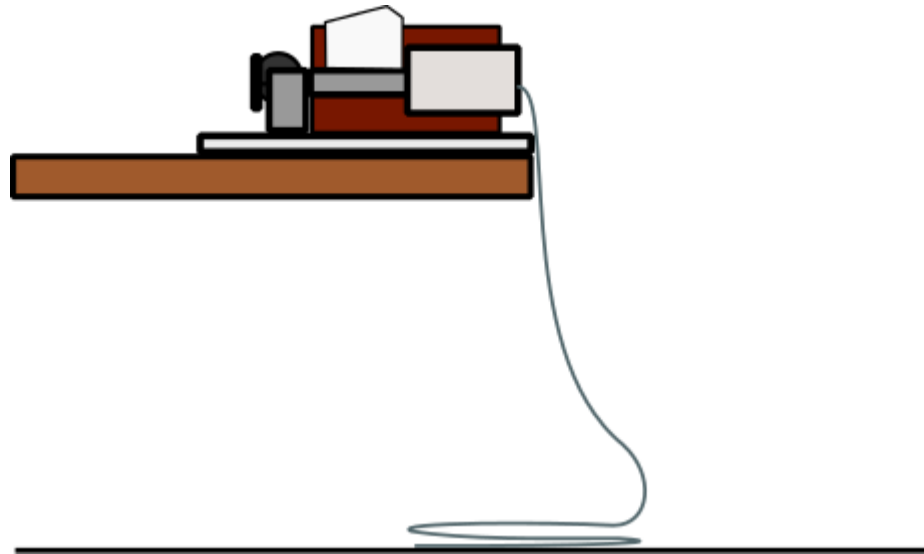


Figure 22. Filament extruder in a steady state setup.

Once the filament extruder was set up to run the basic operating conditions could be explored. First was testing how long it takes for the extruder to get up to extrusion temperature. The Arduino controller was connected to the computer and the temperature was reported by monitoring the COM port that the Arduino connected as. After powering on the power supply the heated barrel heats up to 350 F in roughly 20 min. Once the extruder was up to temperature the filament drive was activated by connecting power to the motor. In

testing the first several feet of filament often has a great deal of variation and is unusable. Once the machine has extruded several feet and settles into steady state operation the consistency improves. One notable phenomenon is that as the molten HDPE exits the nozzle the diameter of the extrusion expands to greater than the exit diameter of the nozzle. Expansion of the filament during extrusion caused the initial run of filament to be oversized. Scaling the exit hole according to the ratio of nozzle diameter to filament diameter after expansion proved to close enough to produce usable filament. Consistency of the filament is critical because if it is too thin it will buckle in the print extruder and cause a jam. Likewise if the filament is too thick it will not be able to enter the hot end of the print extruder and it will jam. Throughout the course of testing several changes were made to the system to improve reliability and filament consistency. The original drive sprocket used and material hopper from the senior design team had to be replaced. The drive sprocket was 3D printed and unable to withstand extended operation. A new 3D printed material hopper was needed due to material getting wedged between the hopper and barrel by the auger. To improve filament consistency a hole was drilled directly below the nozzle of the extruder. Previously the filament had to traverse the distance between the nozzle and the edge of the base plate before it could drop to the floor, this caused issue with the filament snagging on the edge of the baseplate creating problems with consistency.

4.3 Prototyper

The prototyper had a considerable number of settings to be adjusted. First the necessary calibrations to get the machine functional were performed. Next determining which operational settings produced the best result was done in order to create a set of

recommended operating parameters. Exploring the tool chain needed to create various parts was also conducted.

4.3.1 System Configuration

First the physical attributes of the prototyper machine needed to be measured or calculated for initial configuration. The dimensions of the build volume needed to be defined in the host software on the computer and in the firmware of the prototyper. It is important that the dimensions in both the host software and the firmware are the same in order to avoid unexpected misalignment problems. The most critical dimension is the tool height. Misalignments of the print extruder height can cause it to run into the print bed causing damage to the print extruder or print bed. Similarly the height of the milling tool must be set correctly in order to avoid breaking the bit or damaging the print bead. Defining the X and Y axis dimensions was fairly simple. The distance each axis could travel from the home position without exceeding the mills travel limits was measured. Values of 150 mm for the X axis and 100 mm for the Y axis were chosen after measuring. It should be noted that the X axis length could be larger for printing, but the X axis length for the milling area would then be off the edges of the build plate.

Setting the height of the print extruder after initial construction was conducted in a few steps. The approximate height of the print extruder at its maximum height was measured to gain an initial value to work with. With the initial dimensions for the printer the host software and firmware were configured for the build area of the prototype. In Repetier host the dimensions needed to be entered into the printer shape tab in the printer settings menu. In the firmware the dimensions need to be used to configure the min and max positions of

each axis as well as the location of the home position. A copy of the config.h file can be found in appendix III. These settings are located in lines 259 – 264 and 275 – 277 of the config.h file for the firmware code.

Several other system parameters needed to be configured before proceeding with anything else. These are end stop configuration, motor steps/mm, and maximum speed and acceleration. End stop configuration consisted of setting the firmware to travel towards the maximum travel of each axis and to only look for end stop switches at the max travel end of each axis. End stop configuration is found in config.h lines 206 -254. With the prototyper using 1/4-20 threaded lead screws and motor/driver combination of 400 steps per revolution it had a steps/mm value of 315.96 steps/mm. Max speed was initially set to 20mm/s but later changed to 10mm/s as the machine simply travel that fast. Max acceleration was set to 1 mm/s². With the initial motion and position settings configured the machine could then be adjusted for use. Setting the print extruder height could then be precisely set by measuring how far off the initial height setting was and adjusting. Using a block of known height how far off the height position was measured. The block used was 50.80 mm (2.000 inches). Over the print bed the print extruder was lowered until its indicated height was the same as the block. Then the print extruder was either lowered or raised depending on whether it was too low or too high. Once the block could slide between the nozzle of the print extruder and the print bed with a small amount of friction it was at the height of the block. The difference between the indicated height and the height of the block can be used to adjust the Z-axis height configuration. It should be noted that small differences in the height can be compensated for in the slicing settings in the host software.

4.3.2 Additive Manufacturing

Once the prototyper's build volume and movement settings are configured, print testing could begin. Testing began by exploring what configuration for the slicing software works best. Configuration began by exploring movement speed. To get an idea of what speeds could be achieved the manual movement controls in the host software were used move each axis of the machine. The speed the machined was ordered to move was increased incrementally until the machine had difficulty. At higher speeds the stepper motor had a tendency to stall, stuttering between steps. Acceleration also had to be adjusted in the firmware because accelerating too quickly caused the motors to stall. An acceleration of 2mm/s^2 was found to be a good balance between fast acceleration and top speed. For a single axis moving at a time movement speed maxed out near 8mm/s . Next operational movement speed was testing by having the machine attempt to follow a tool path for printing a part. Having the machine traversing a complicated path showed that the machine was not capable moving as quickly when using both axis and making speed changes. 4.5mm/s turned out to be the maximum travel speed without risking motor stutter. There are a number of factors limiting the speed of axis movement. One significant factor is the larger amount of friction in a lead screw system versus a belt system. The larger friction combined with the finer resolution necessitate high motor speed and torque. Stepper motors have decent torque at slow speeds but torque drops off quickly as speed increases. Another factor is resolution itself. A possible problem is that with the much higher number of steps per mm the controller has trouble keeping up with sending the signal pulses fast enough to the stepper driver. There are a couple signs that point to the controller struggling to keep up. Switching the stepper drivers from quarter stepping to half stepping allowed for a modest

operating speed increase due to fewer steps per mm. Operating more than one axis at a time results in a large drop in the maximum speed possible without motor stutter. This is most noticeable when following a diagonal or curved path.

Configuring the parameters for each print depend on the material being used and the desired quality of the print. The filament used affects a few key parameters. The diameter has a great deal of effect on the resulting print. Commercially produced filament is fairly consistent so once the diameter is set in the filament settings it can be left alone. Filament produced by the filament extruder varies much more, and it should be measured before use. Improper filament diameter configuration can lead to problems such poor layer adhesion if it is set larger than what the filament diameter actually is. If the configuration is set smaller than what the filament is then the print extruder can end up jamming during the print. Which material the filament is made out of will affect the temperature settings. There are two main temperature settings, the first layer temperature and the print temperature. The first layer can sometimes adhere better to the print bed if it is printed at a slightly higher temperature. PLA worked well with both set to 225 C. HDPE worked best with a first layer temperature of 253C and a print temperature of 240 C.

Other print settings such as layer height, number of shells, and support material are changed frequently depending on the print. Layer height affects the resolution of the layer height and can be set anywhere between .15 and .25 mm. In testing a recommended set of configurations were settled upon, they can be seen in figures 23 - 28.

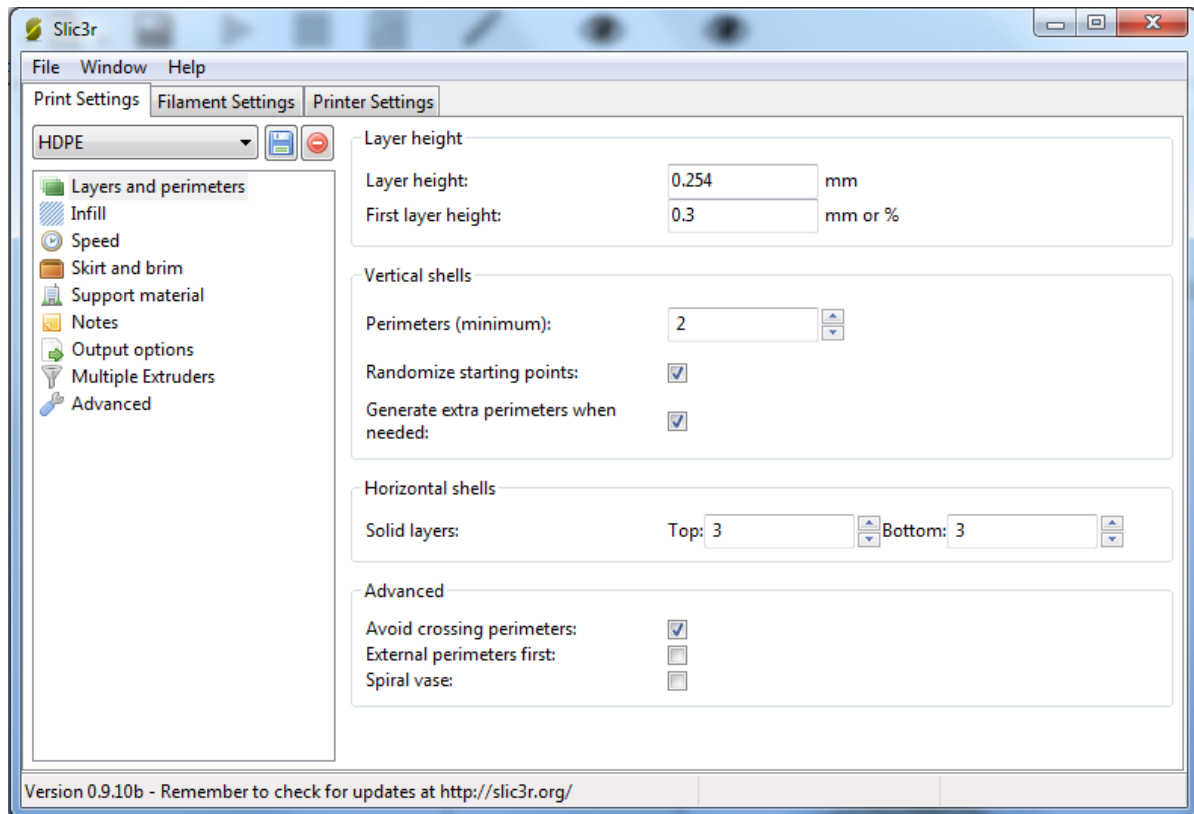


Figure 23. Layer and perimeter print settings.

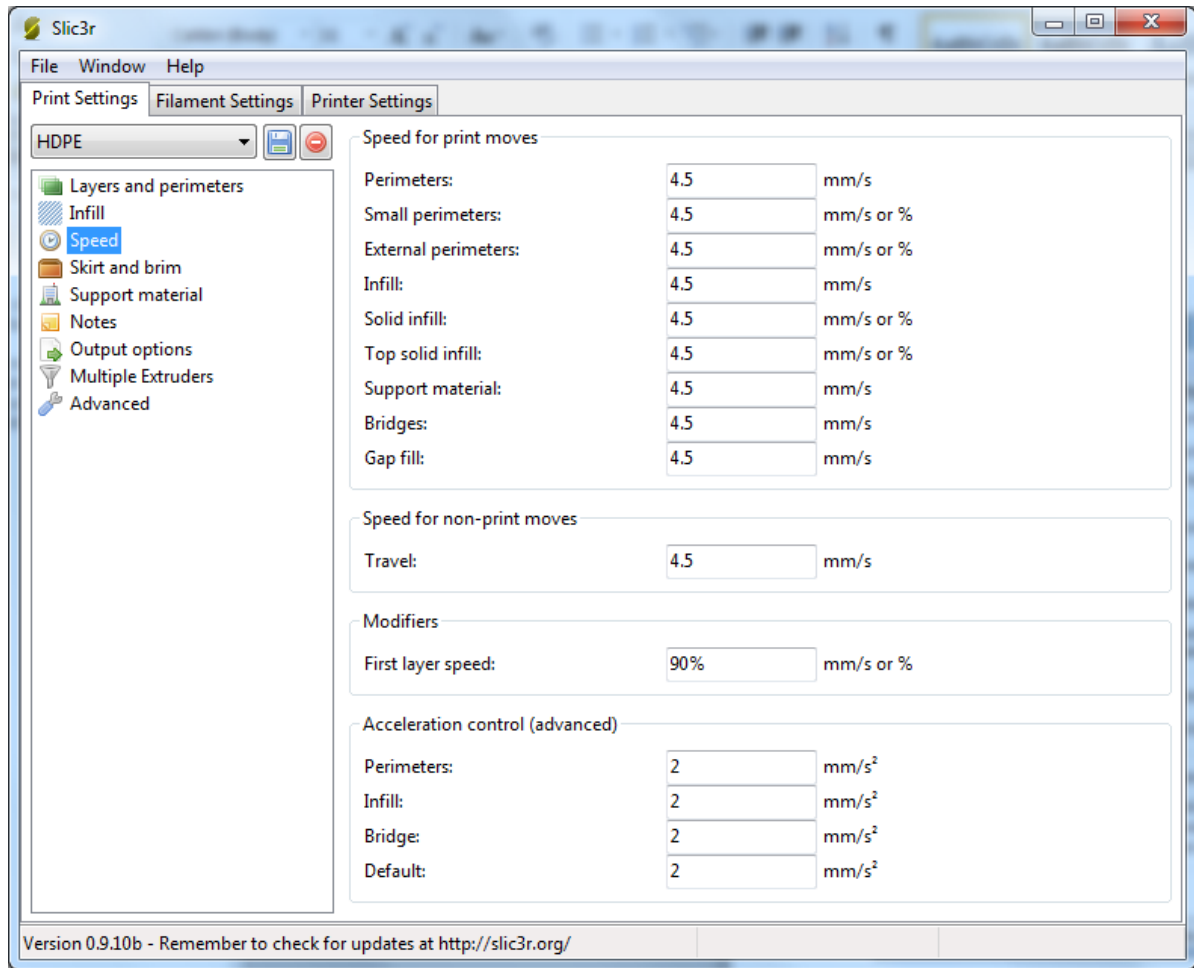


Figure 24. Print speed settings.

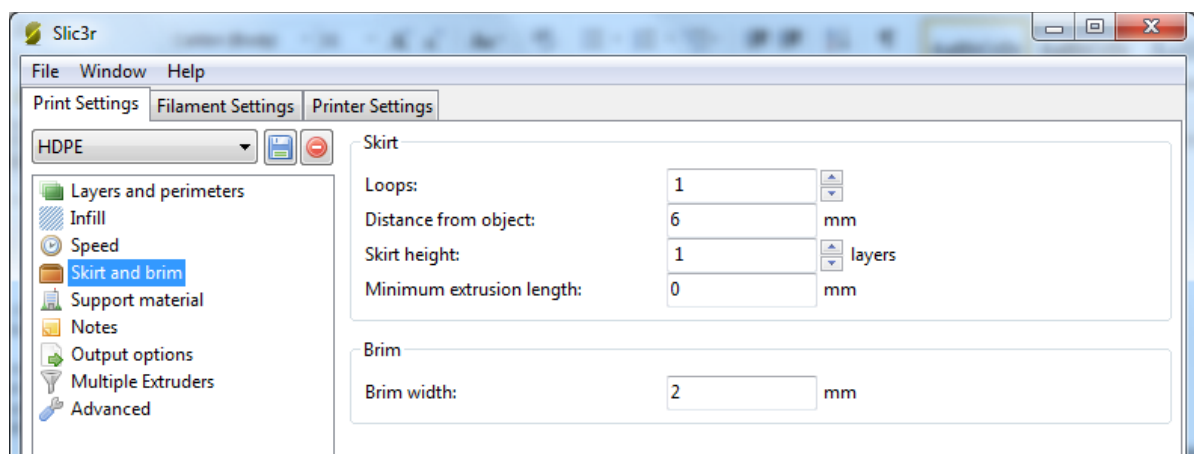


Figure 25. Skirt and brim print settings.

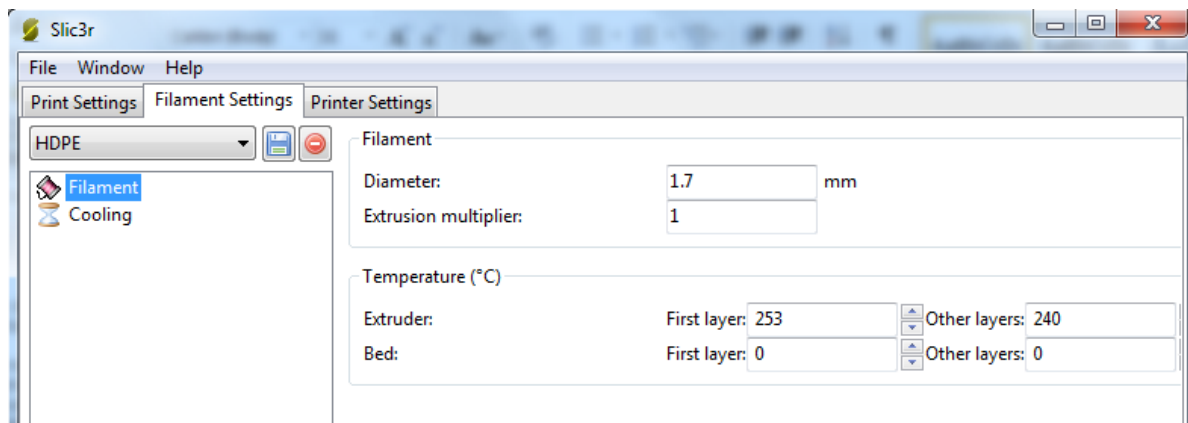


Figure 26. Filament settings for HDPE filament.

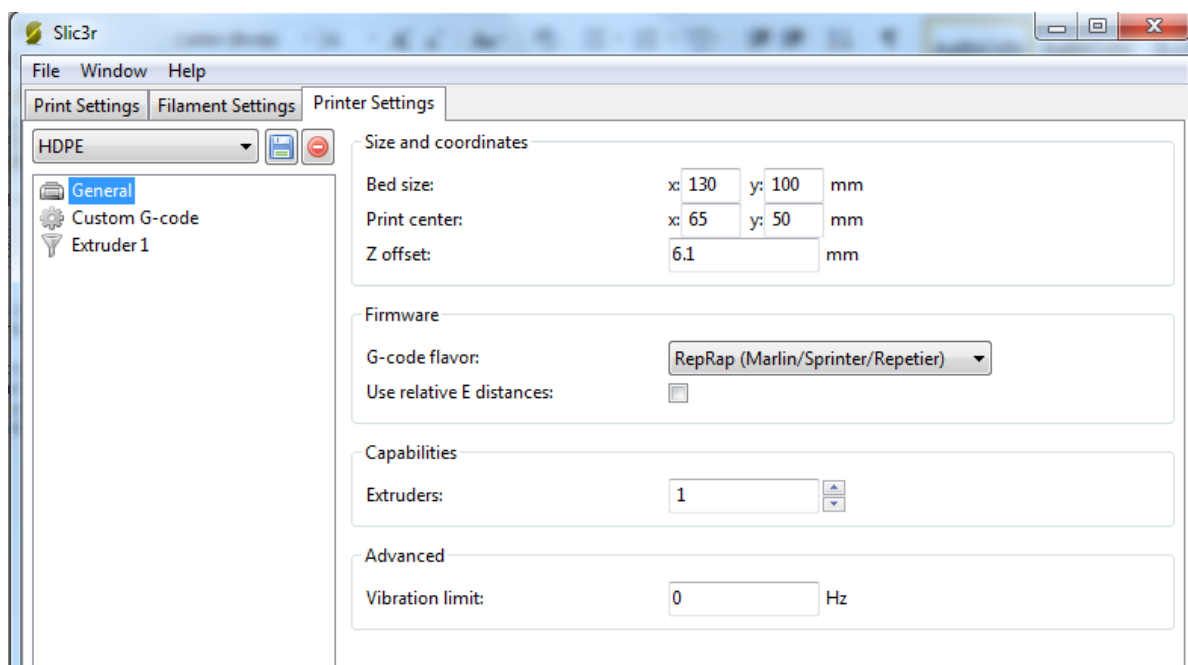


Figure 27. Printer size settings.

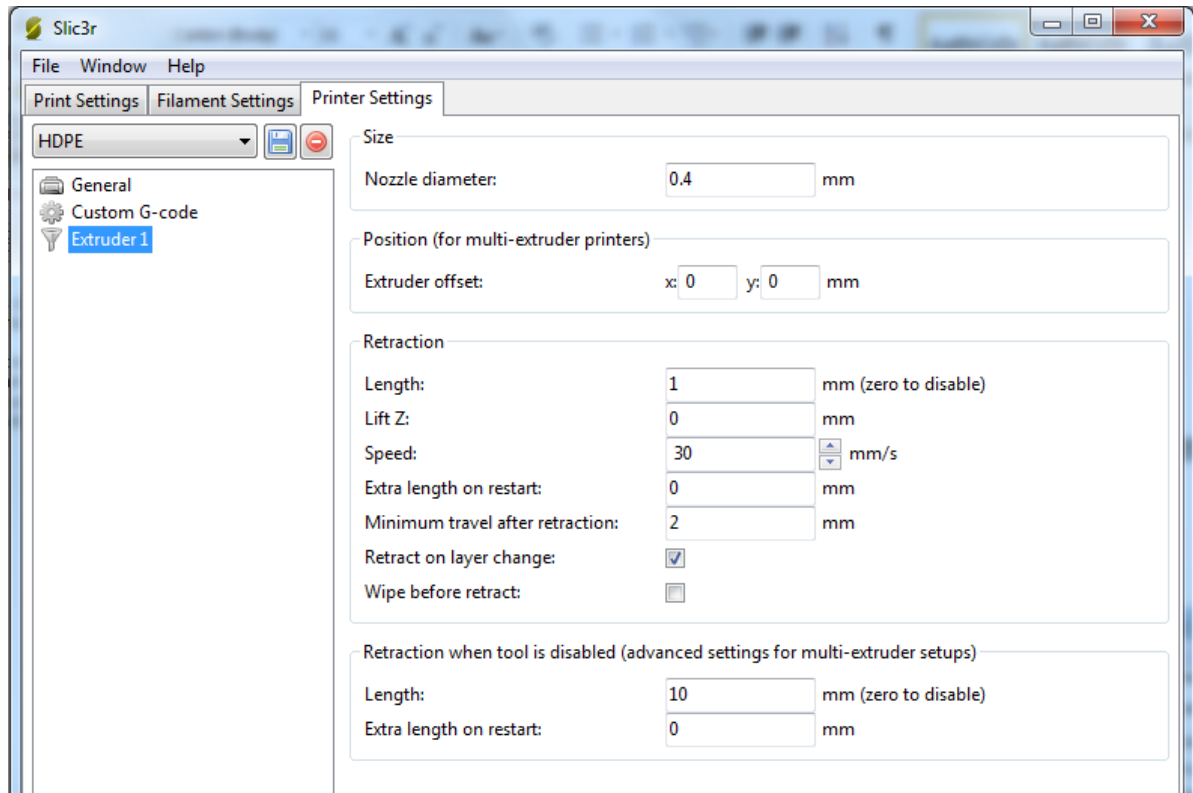


Figure 28. Extruder settings for the prototyper.

Test printing was done using commercial PLA filament and HDPE filament. PLA filament was able to provide a baseline for the performance of the prototyper to make sure it worked. A number of test prints were conducted. The prototyper worked but had a few issues. Primarily speed was the biggest issue, but that was expected with the lead screw system. The low speeds lead to a need for using a minimum of 2 shells. If a print only used one shell the outer layer would have small gaps in the surface. Examples of this effect can be seen in figure 29.

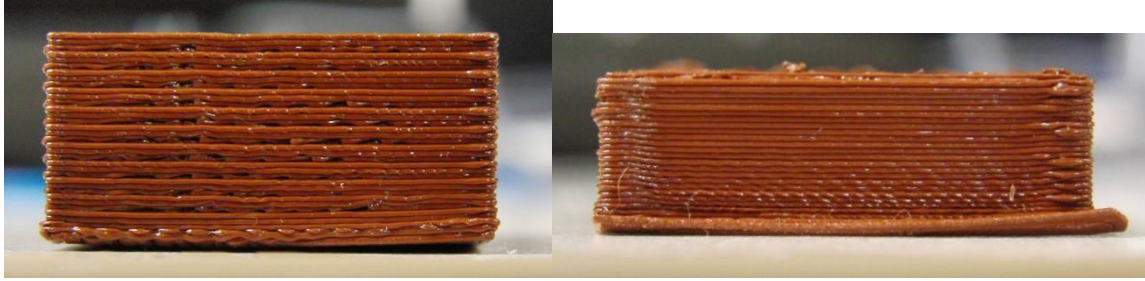


Figure 29. Left single shell with gaps, Right double shell, both using PLA.

The gaps in the single shell occurred where the infill intersected the shell. With the slow movement the printer nozzle stays over the area long enough to partially melt the shell and drag it with it as the nozzle moves away. Another speed related issue is blobs at sharp corners. This is caused by the slow acceleration of the movements. Settings do exist in the slicer to help mitigate the problem, but the acceleration is low enough that it cannot fully alleviate the problem. Warping of the bottom of the print is also present, but that is a common problem with printers running without a heated bed.

Some success has been made using HDPE filament although it has been more challenging. Examples of the increased challenges of HDPE include a higher variation in the filament diameter, issues with layer adhesion, and more severe warping. Variations in filament diameter can lead to an inconsistent finish and in severe case jamming of the print extruder. The inconsistency of the HDPE filament from the filament extruder has been one of the biggest problems. If the filament is made so that it stay small enough be fed through the print head it starts exhibiting problems with buckling in the print extruder. This problem could probably solved by moving to a 3mm system. Layer adhesion problems can be minimized by increasing the printing temperature to 253 °C for the first layer and 240 °C for the subsequent layers. With HDPE a balance has to be struck between extruding hot enough to reliably adhere and keeping the previously printed material solid enough to not deform

while printing. One common way to solve this problem for other materials is to add a fan that cools the part as it was printed. A filament cooling fan was added to the system and found to significantly help in achieving this balance allowing for smaller features to be printed. Even with the performance improvements from adding the fan printing fine details with HDPE is more difficult than using PLA. The tendency for fine details and sharp corners to get deformed by the dragging of freshly deposited plastic can be seen in figure 30 below.

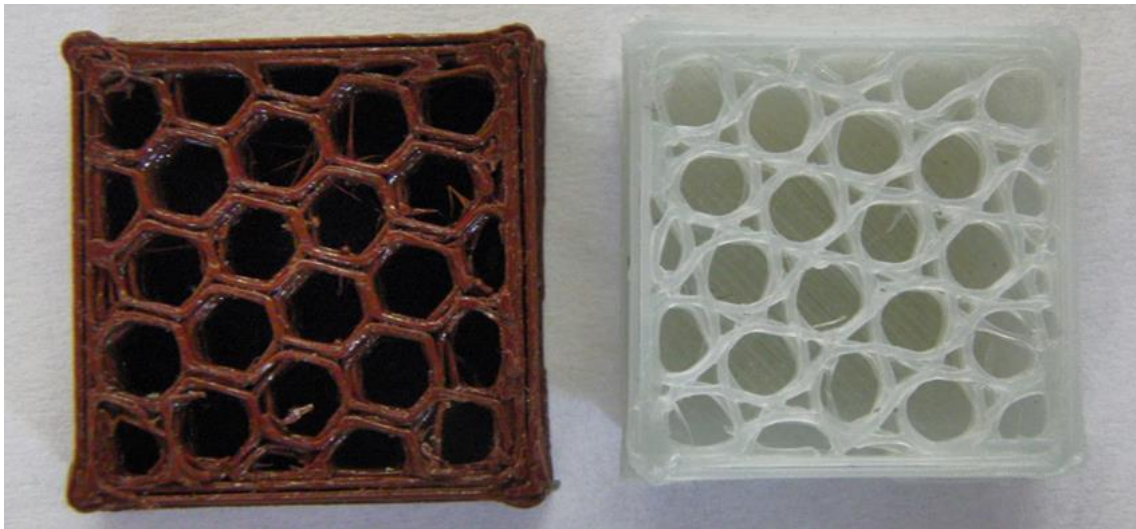


Figure 30 The interior structure of a PLA, left, and HDPE part, right.

Both parts in the figure were printed with the same Gcode. The part on the left was printed using brown PLA and the part on the right was printed with HDPE. The hexagonal fill pattern in the PLA part has much sharper corners. In the HDPE part has gaps where the corners of the hexagons are supposed to meet. This is from the still molten HDPE getting pulled on as the extruder changes directions.

Another challenge in using HDPE is keeping it secured to the print bed during printing. In order to help the HDPE to stick to the print bed poly propylene was used to make the print beds. While prints would stick to it the print beds often suffered minor surface damage. The

damage came from the print partially melting to the bed. As using a tape that 3D printed parts will stick to is a common solution with other materials a polypropylene tape was sought out. It was found that the backing of common packaging tape is often made from polypropylene. Printing on poly propylene tape allows for the HDPE prints to stick to the print bed while minimizing the damage to print bed surface.

There are many significant obstacles in using HDPE for 3D printing but they can be overcome. A few successful test pieces such as the octopus in figure 31 were made.



Figure 31. An example of a HDPE test print.

4.3.3 Subtractive Manufacturing

The subtractive manufacturing capabilities were explored as well. A large part of the testing was finding a suitable tool chain for use with the CNC milling system. One area where the software projects surrounding the RepRap project are lacking is robust CAM software. Part of the issue is the G-code implementation in RepRap firmware doesn't adhere to G-code standards very closely. The basic motion commands work normally, but many of the additional commands have been repurposed or not implemented. An attempt to create a generic tool path in MasterCAM and remove any unnecessary code proved fruitless. There is a basic tool chain that can be used to generate 2D CNC routing paths. This tool chain uses

a web based program called MakerCAM to create toolpaths from a vector graphic. First a vector image of the paths desired needs to be created in a program such as Inkscape or other vector graphics software. Then the file needs to be uploaded to MakerCAM. Tool paths can be created by selecting the paths from the vector graphic and then selecting the type of tool path desired and entering tool and speed settings. Once the tool paths are created they need to be calculated to generate the G-code. With the paths calculated the G-code can be exported and downloaded by the user. Using this process it was possible to mill a grid and several shapes into one of the print beds. The engraved print bed can be seen in figure 32 below.

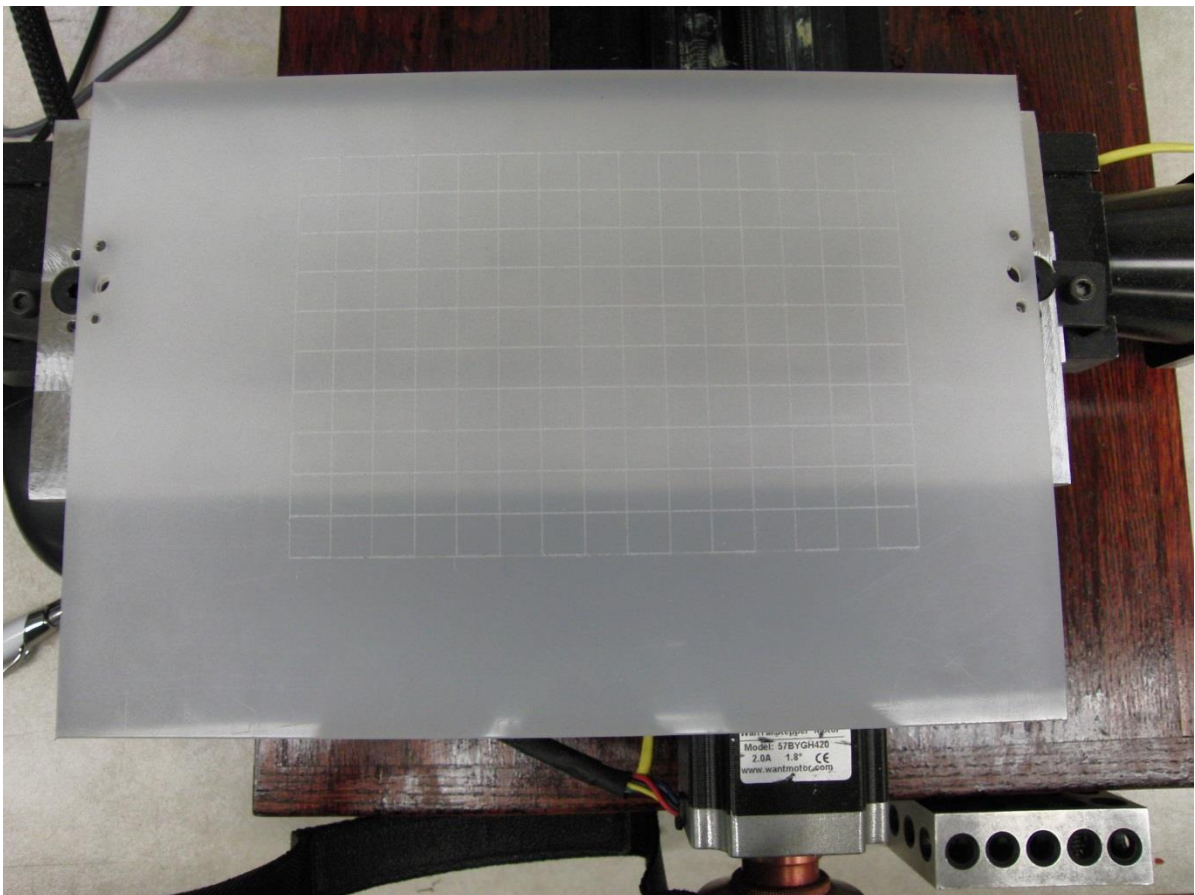


Figure 32. Print bed with a grid engraved into it.

Chapter 5. Using the System

Throughout the testing of the prototyper lessons were learned and recommended practices established. This chapter will go over the recommended procedures for using the machines developed for the system. Recommended design practices for designing parts that are intended to be 3D printed will also be discussed. Section 5.1 will cover the instructions on how to operate the shredding machines. Section 5.2 will cover the instructions on how to use the filament extruder. Section 5.3 will cover using the prototyper including basic usage, additive manufacturing, and subtractive manufacturing. Section 5.4 will cover design practices for parts intended to be made with a FDM 3D printer.

5.1 How to use the shredder

The shredder is capable of converting empty washed milk jugs into small uniform pieces. This process has two main steps, cutting up the milk jugs into sheets and running the sheets through the shredder.

Preparation of a milk jug for shredding can be done in a short time with a pair of scissors.

1. Make sure that the jug has been thoroughly cleaned.
2. Cut out the section of the jug with the label attached and discard it, as seen in figure 33.



Figure 33. Cutting out the label.

3. Cut off the handle of the milk jug, as seen in figure 34.



Figure 34. Milk jug with handle cut off

4. Cut off the bottom of the jug, cutting along the corner of the bottom, like in figure 35.

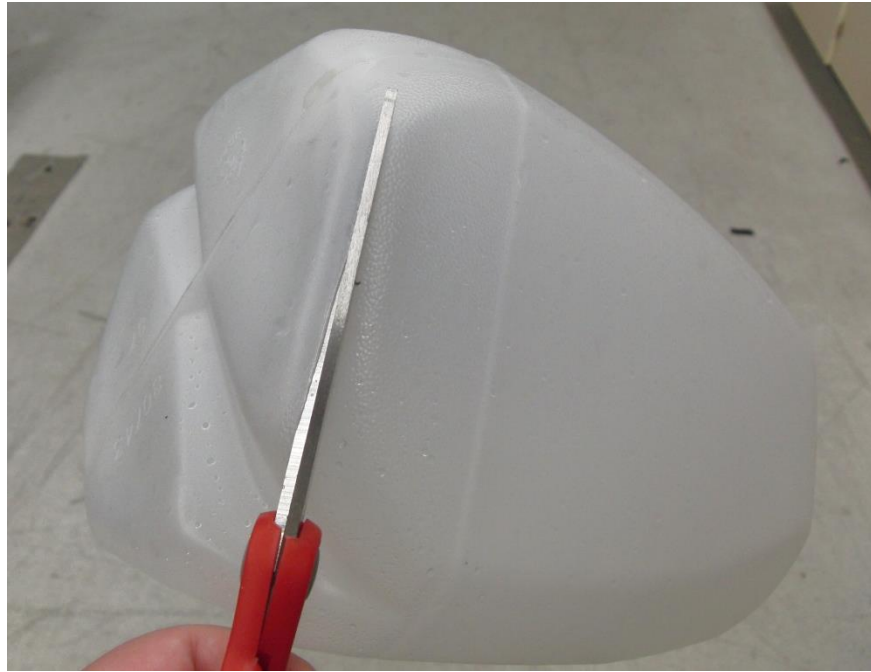


Figure 35. Cutting the bottom off.

5. Cut the jug into sheets along its corners, as seen in figure 36 below.



Figure 36. Cutting the jug along its corner.

6. Now there should be six pieces the bottom, the handle, and 4 sides

Once prepared the pieces of milk jug can be run through the shredder. Operating the shredder is done by following these steps:

Caution: The shredder has exposed shredding teeth in its opening. Take care and keep fingers, limbs, and loose articles away from the shredding teeth.

1. Press and hold the red button on the shredder.
2. Place pieces individually into the top of the shredder, as seen below in figure 37.



Figure 37. Piece of milk jug being put through the shredder.

3. Run pieces too large to fall through the grate through the shredder again until all pieces fall through the grate. An example of a piece that needs to be run through again can be seen in figure 38.



Figure 38. Incompletely shredded plastic sheet.

4. Empty the drawer of the shredded pieces when done or as the drawer becomes full, as seen in figure 39.



Figure 39. Shredded plastic in the collection tray.

Sometimes the shredder can bind up even though only one piece was placed into the shredder at a time. Often it can be solved by releasing the button and then holding it down again. The machine will once again turn on the motor. Sometime it may take a few attempts before the machine clears itself.

5.2 Using the Filament Extruder

The filament extruder is still somewhat experimental but can be used to produce HDPE filament. Filament production follows the general process of connecting it to the computer, turning on the heater, starting the extruder drive once hot, and monitoring the production of filament. The steps to the process are as follows:

Caution: Operating the filament extruder involves high temperatures. Do not touch the nozzle, molten plastic, or any other part that may be hot.

1. Connect the Arduino to the computer
2. Open the Arduino IDE
3. Make sure it is set to the COM port that the Arduino is using, as seen in figure 40.

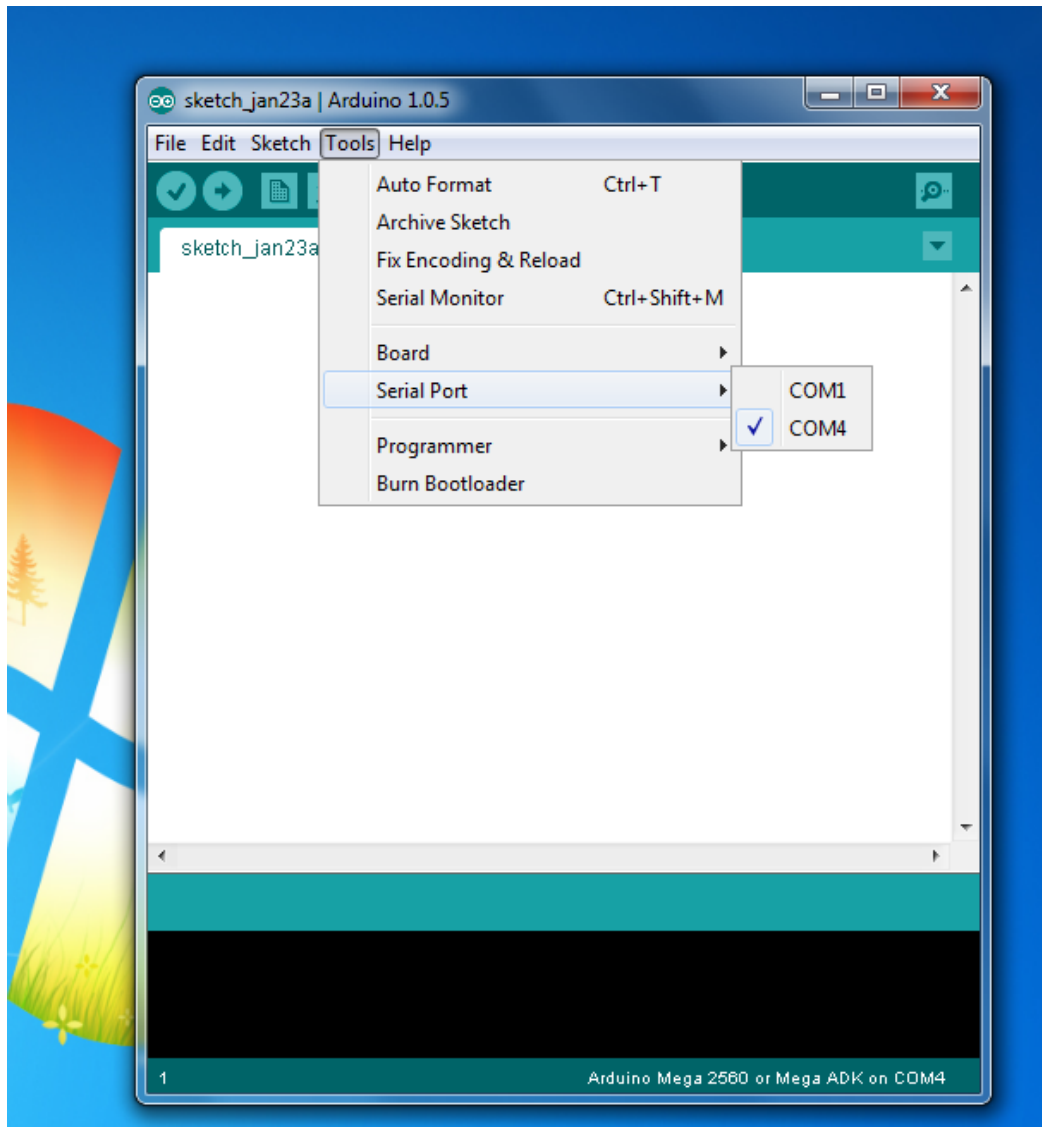


Figure 40. Selecting the COM port.

4. Open the serial monitor. It should be constantly updating the temperature. The temperature is reported in degrees Fahrenheit. The serial monitor can be seen in figure 41.

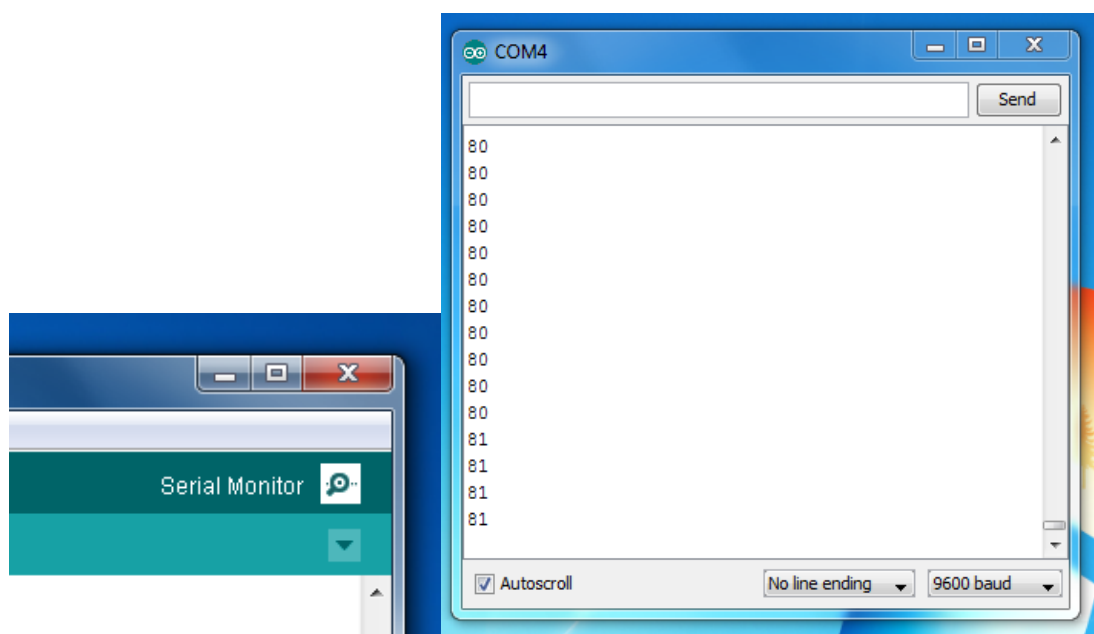


Figure 41. Serial monitor button and temperature display.

5. Turn on the power to the filament extruder using the switch on the power supply.
The temperature should now begin to increase
6. Monitor the temperature and wait for it to reach around 350 degrees. What the serial monitor will display when it is at operating temperature can be seen in figure 42.

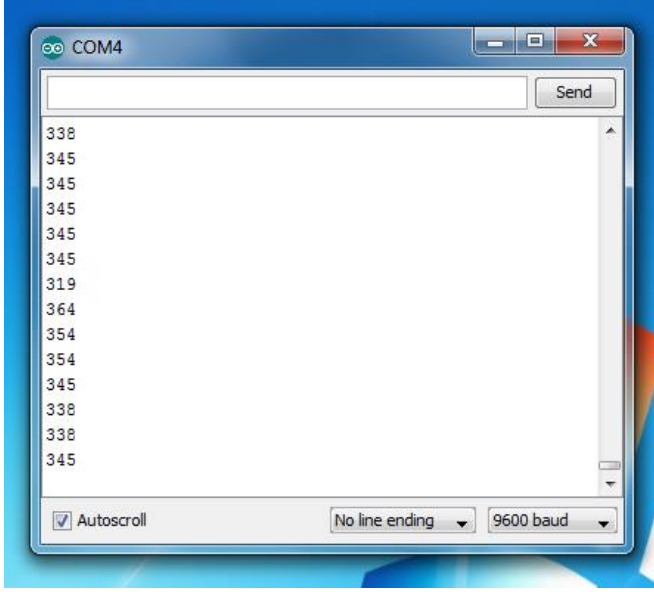


Figure 42. Serial monitor displaying running temperature.

7. Make sure the hopper is full
8. Turn on power to the drive motor by attaching the red clip to the motor as seen in figure 43.

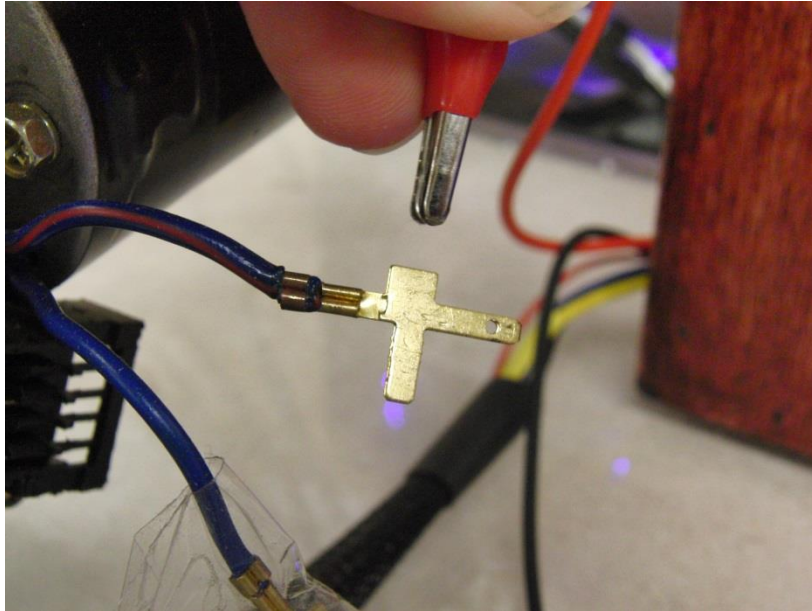


Figure 43. Connecting power clip.

9. Watch for plastic to be extruded from the nozzle.
10. Using a small pair of pliers guide the filament into the hole in the baseplate as seen in figure 44 below.

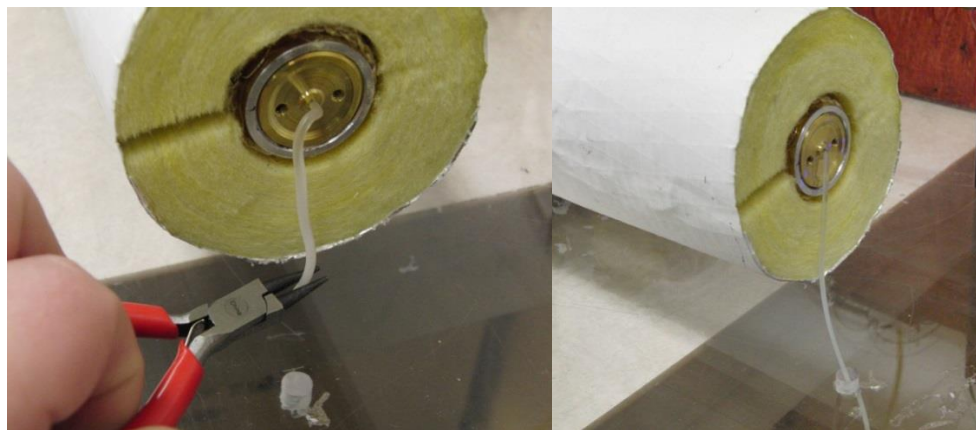


Figure 44. Guiding the filament into the hole in the baseplate.

11. Watch the filament to make sure that the filament doesn't snag when it's passing through the baseplate or coiling up on the ground.
12. Make sure the hopper stays full.
13. Disconnect the drive motor when done.
14. Turn of power to filament extruder.
15. Disconnect the Arduino for the computer.

5.3 Prototyper operation

To make parts using the prototyper there are few things that need to be known. First basic system use procedures such as homing the machine and manual movement, using tool head controls, measuring and setting tool height, and loading filament. Next, how to use the prototyper to 3D print parts. Finally, how to use the CNC milling capabilities.

5.3.1 Basic Usage Procedures

5.3.1.1 Axis Homing and Manual Movement

First the basic task of operating the prototyper is how to turn it on and get it ready for use by homing its axis.

NOTE: The printer control box has a large red reset button on top of the box. This is so that the user can reset the controller when something goes wrong such as if it is about to crash into the print bed. If the reset button is used the printer will need to be sent to the home position before doing anything else with the prototyper. What the button looks like can be seen in figure 45.

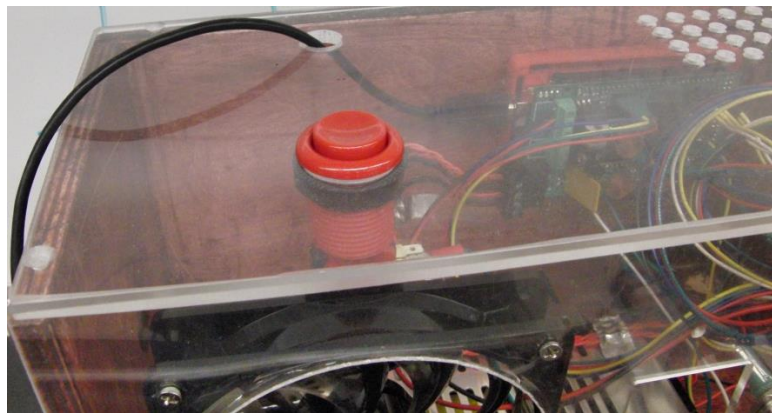


Figure 45. Reset button on the control box.

Turning on and homing the prototyper

1. Turn on the prototyper by flipping the switches on the back of the prototyper control box and the tool head control box. The lights and fan on the control box should come on, and the fan attached to the print head should also turn on.
2. Open the program Repetier Host on the control computer.
3. Click on the connect button in the upper left of the program window as seen in figure 46 below.

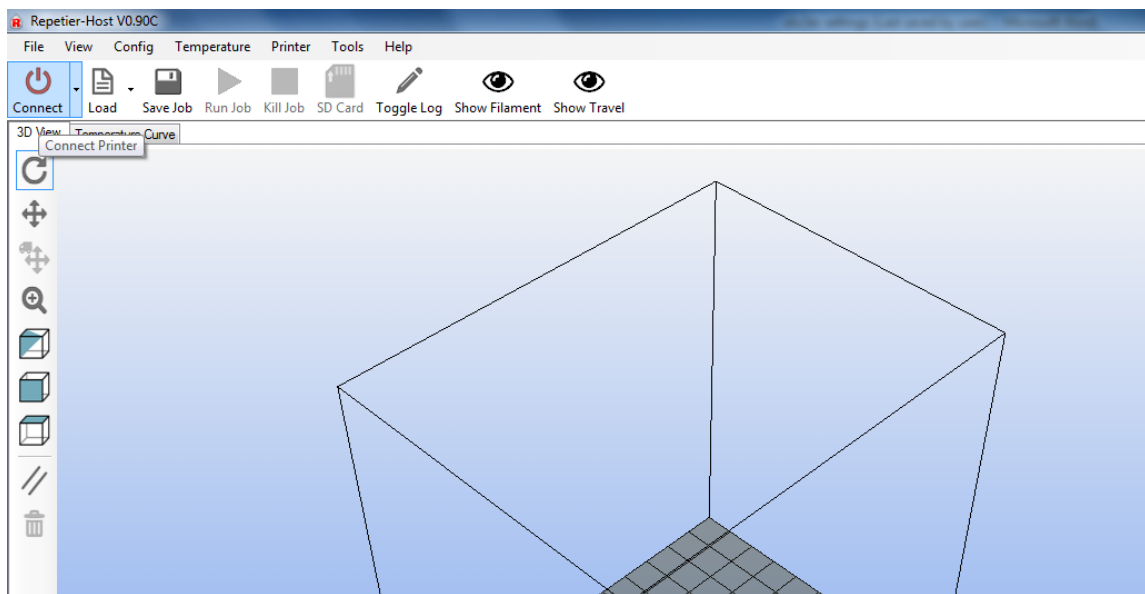


Figure 46. Connect to printer button in Repetier Host.

4. Click on the manual control tab. This tab allows for manual control of the prototyper's printer hardware. What the manual control tab looks like can be seen in figure 47.

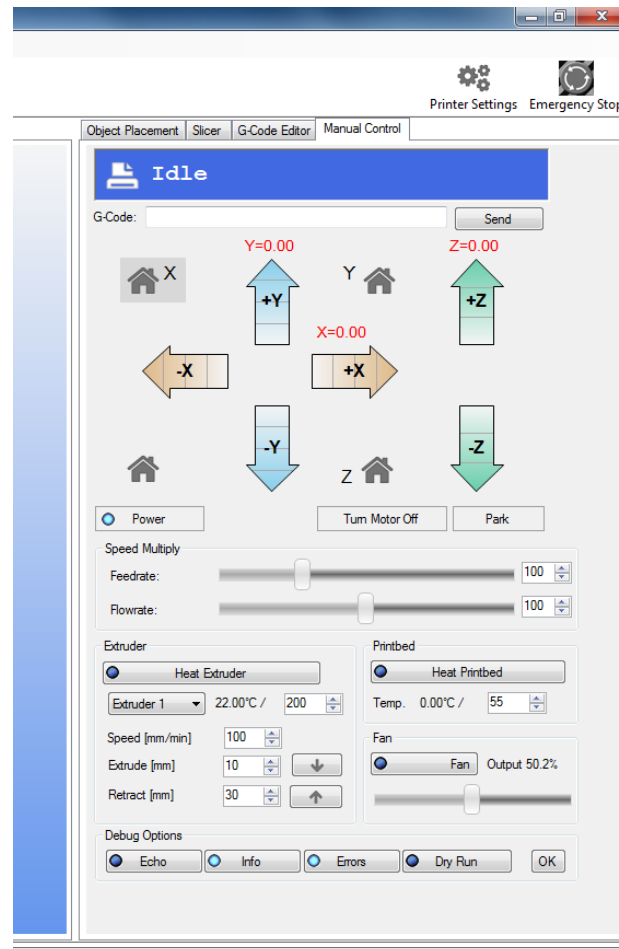


Figure 47. Manual control tab.

5. Using the handle on the end of each axis move each axis a little bit away from the home position if the axis is at the home position.
6. Click on the axis home button.
7. Watch the machine home each axis and be prepared to hit the reset button if something goes wrong.

Manual movements can be made using the manual control interface by clicking on the button corresponding to the desired axis direction and increment. The position displayed by

the manual control window is where the machine is supposed to be after the movement is complete and not the current position.

5.3.1.2 Using the Tool Head Controls

The tool head controls two functions, switching between manufacturing modes and controlling the spindle speed. As it has two functions it has two controls and a status light.

They can be seen in figure 48.

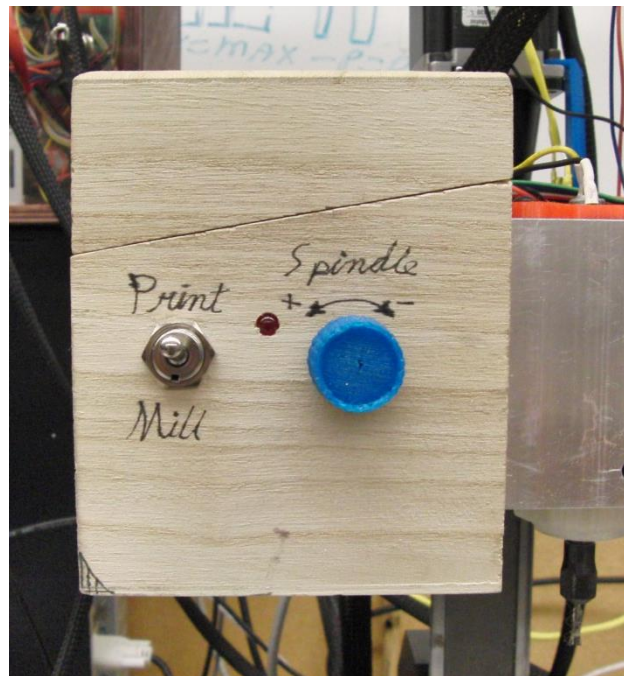


Figure 48. Controls for the tool head control box.

Changing mode:

1. Make sure that the spindle speed is set to its minimum.
2. Flip the mode switch to the desired mode.
3. Wait for 10 seconds. The indicator light will be illuminated while changing modes.
4. Set the relevant height settings for the manufacturing mode going to be used.

The motor controller used needs to go through an arming sequence before it will run the spindle motor.

Arming the spindle motor:

1. Start with the speed set to its minimum
2. Turn the speed up to its maximum.
3. Wait two seconds
4. Set the speed back to minimum.
5. Wait two seconds
6. Set the motor to desired speed setting and the spindle should start

If the speed is returned to minimum it will not immediately start the motor again when the speed is turned back up. There is a 10 second delay before the motor starts back up.

5.3.1.3 Measuring Print Nozzle Height Offset

Every time the tool head mode is changed the height of the nozzle can change slightly due to the repeatability of the linear servo. Pushing on the extruder with too much force can cause it to shift. The nozzle height needs to be measured any time that the nozzle likely moved. A block of a known height is needed and for testing a 2.000" (50.80mm) block was used.

Measuring the nozzle height offset:

1. Move the nozzle over the print area using the manual control window
2. Move the Z-axis to the height of the block. As can be seen in figure 49 the indicated height and actual height may be different.

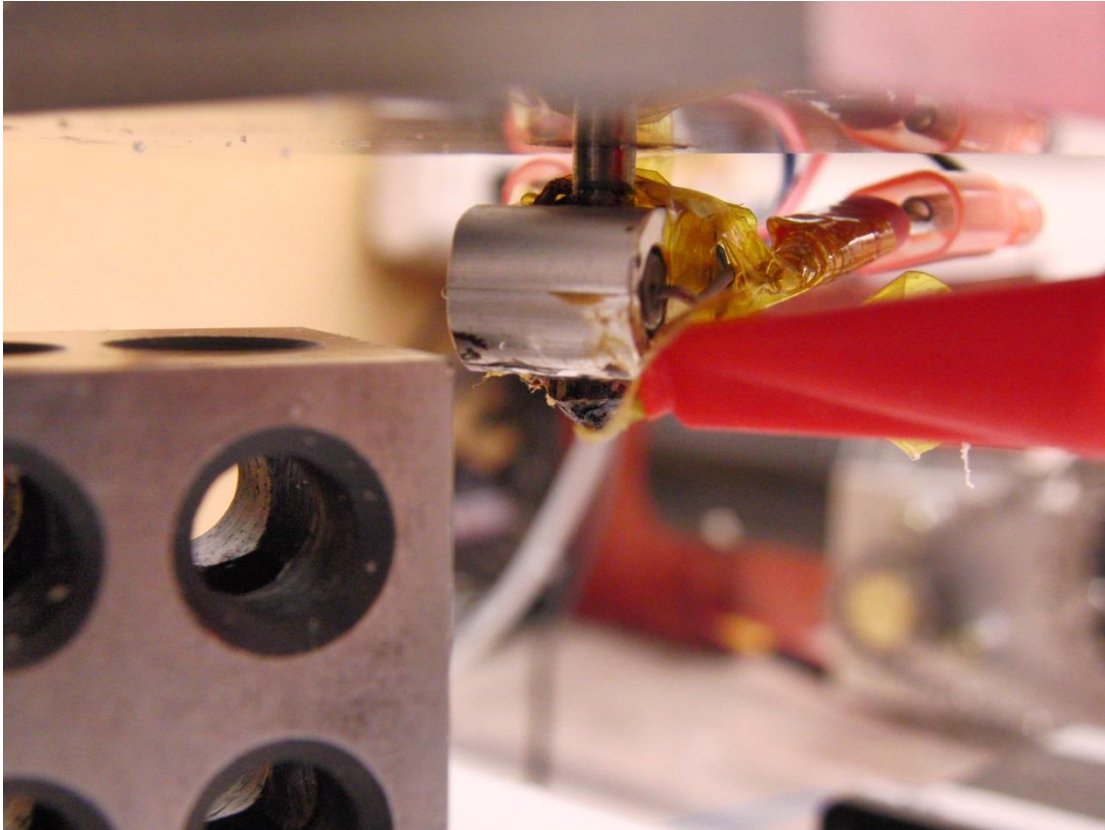


Figure 49. Block next to nozzle.

3. Check if the block can slide underneath with a small amount of friction.
4. Increase or decrease height of the Z-axis using small increments until the block can fit underneath with a small amount of friction like seen in figure 50.

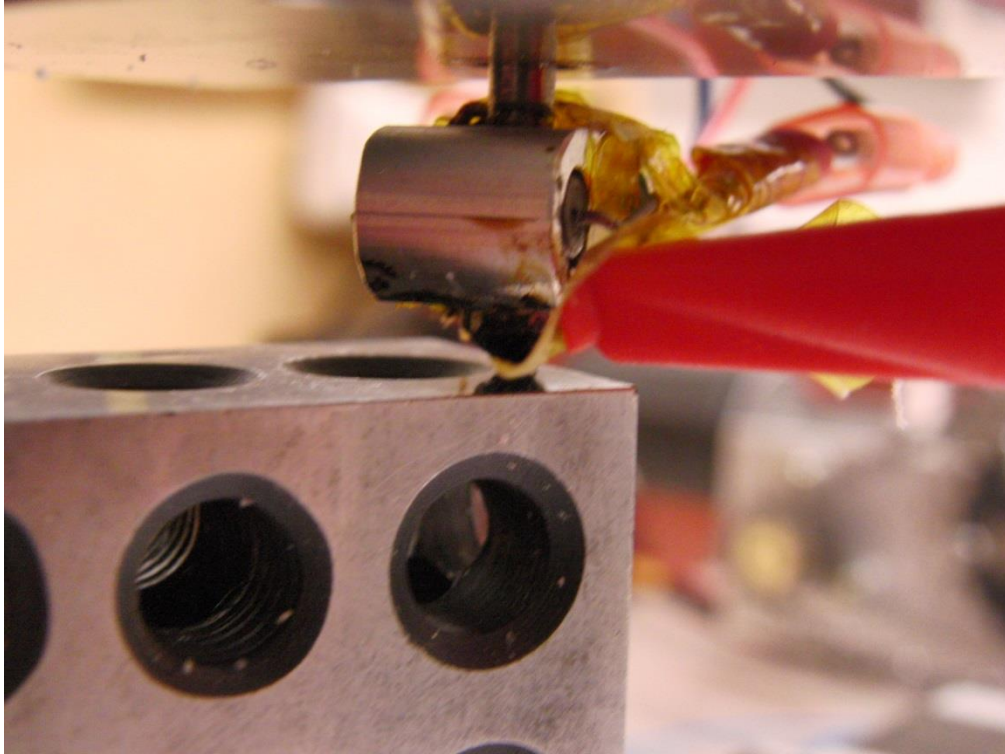


Figure 50. The block can now slide under the nozzle.

5. Subtract the height of the block from the final height of the Z-axis. This is the nozzle height offset
6. Open the slicer settings window and navigate to the printer settings tab as seen in figure 51.

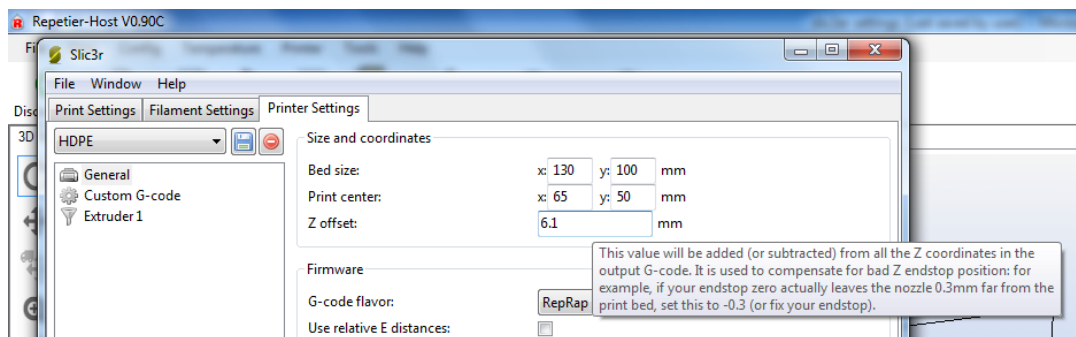


Figure 51. Nozzle height setting in Repetier Host.

7. Enter the nozzle height offset in the Z offset setting.

5.3.1.4 Setting Milling Tool Height

With the interchangeability of milling bits the height of each bit must be set whenever it is placed in the spindle. Setting bit height uses a block of known height like that used for measuring nozzle height

Installing and setting the height of a bit in the spindle;

1. Move the spindle over the print area using the manual control window
2. Move the Z-axis to the height of the block.
3. Insert the milling bit into the spindle collet as deep as allowed, like in figure 52.

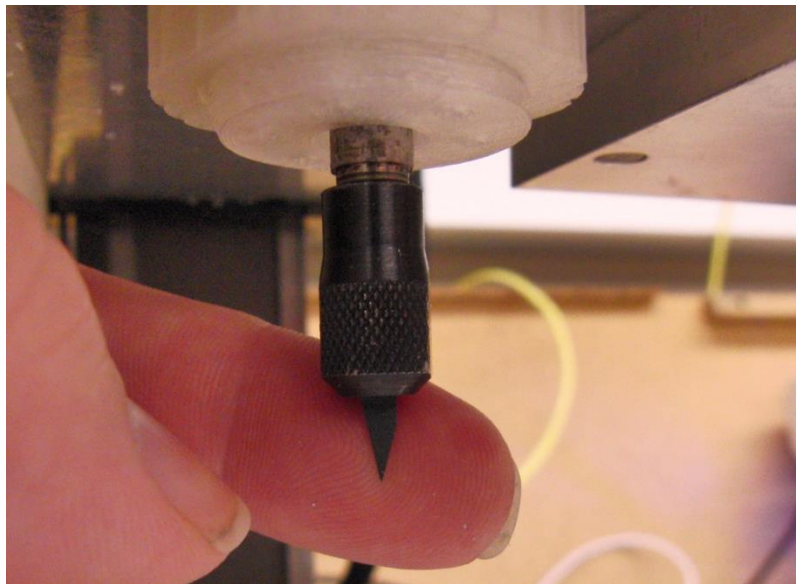


Figure 52. Tool inserted into the collet.

4. Place the block beneath the tool
5. Pull the milling bit out of the collet until its tip touches the top of the block as seen in figure 53.

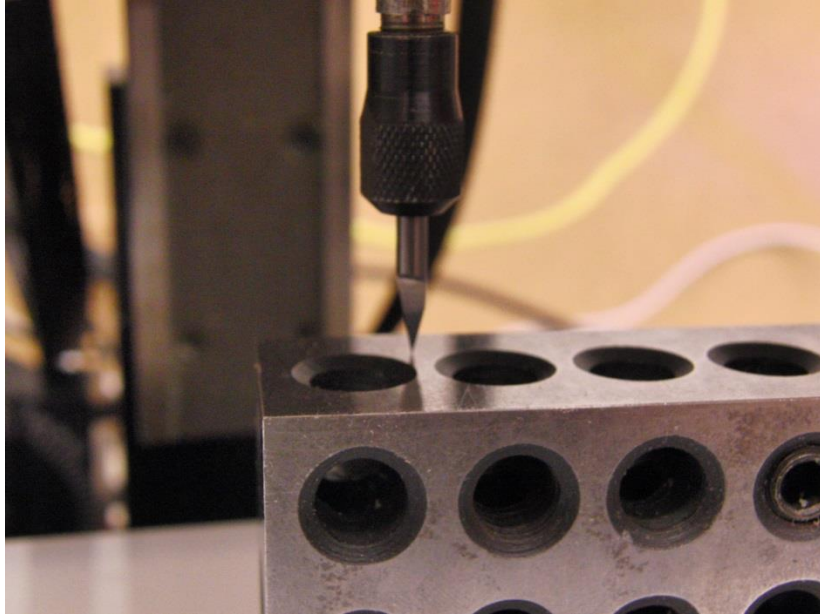


Figure 53. Tool set to the height of the block.

6. Place a hex wrench or similar tool in the hole in the face of the tool head block to keep the spindle from turning. This can be seen in the following figure.

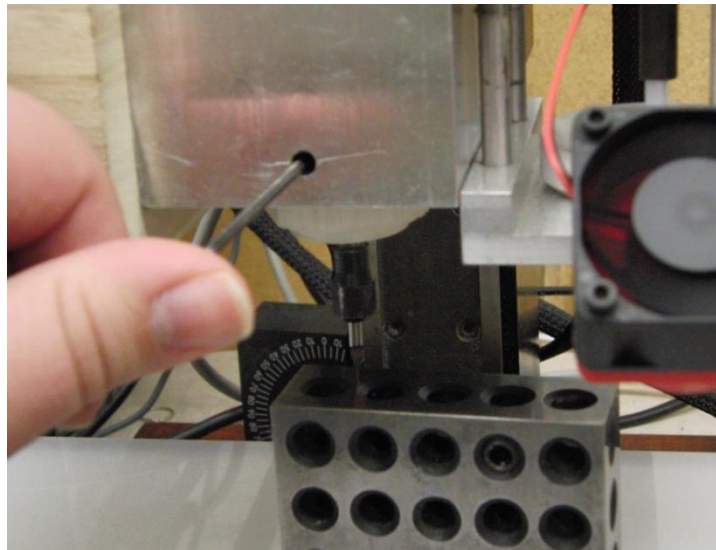


Figure 54. Tool inserted to keep spindle for turning.

7. Tighten the collect to secure the milling bit.
8. Remove the block and hex wrench.

5.3.1.5 Changing Filament

In order to change filament follow this procedure.

1. Turn on the print extruder heater using the manual control window. The heater control can be seen in figure 55.

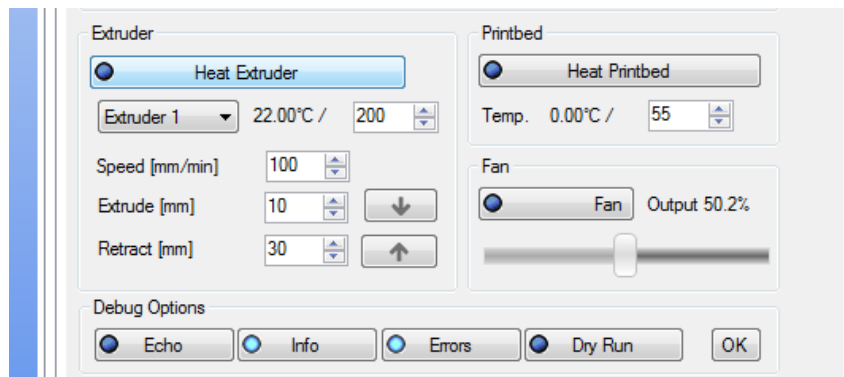


Figure 55. Heat control in the manual control tab.

2. Wait for the hot end to heat up.
3. Make the extruder retract the filament using the manual control window to pull the filament out of the hot end.
4. Relieve the pressure pressing the filament against drive wheel by pulling the spring loaded wheel away from the drive wheel as seen in figure 56.

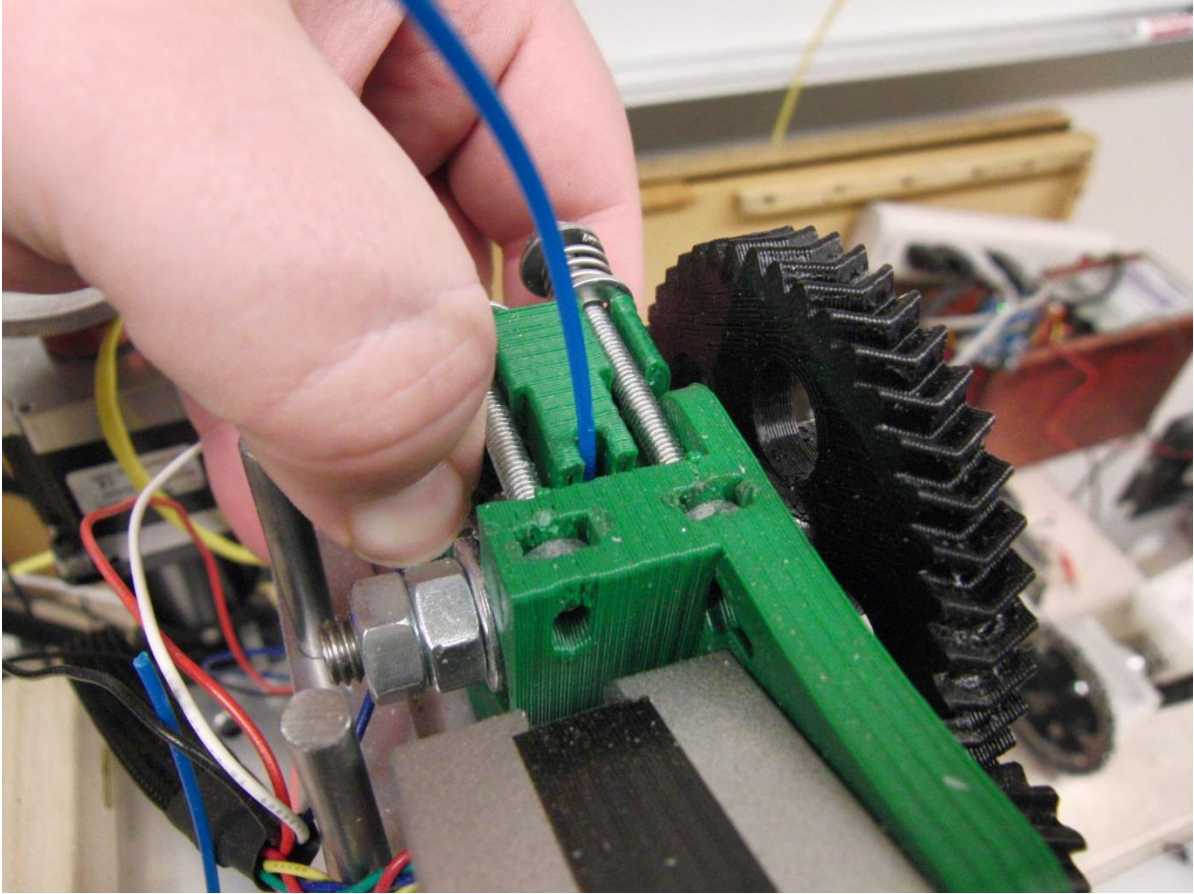


Figure 56. Relieving pressure so filament can be removed.

5. Pull the filament out of the extruder
6. Insert the new filament as far as it will go.
7. Release the spring loaded wheel.
8. Command the extruder to advance filament until it comes out the nozzle.

5.3.2 3D Printing with the Prototyper

Once the prototyper has been setup and is ready to go, parts can be printed. For these instructions a cube will be printed, and it is assumed that the file for the part to be printed is already available as an STL file.

1. Go to the part positioning tab in Repetier Host

2. Click on the load button in the upper toolbar.
3. Navigate to the desired part file and click open. The part should now appear in the position display window. This can be seen in figure 57.

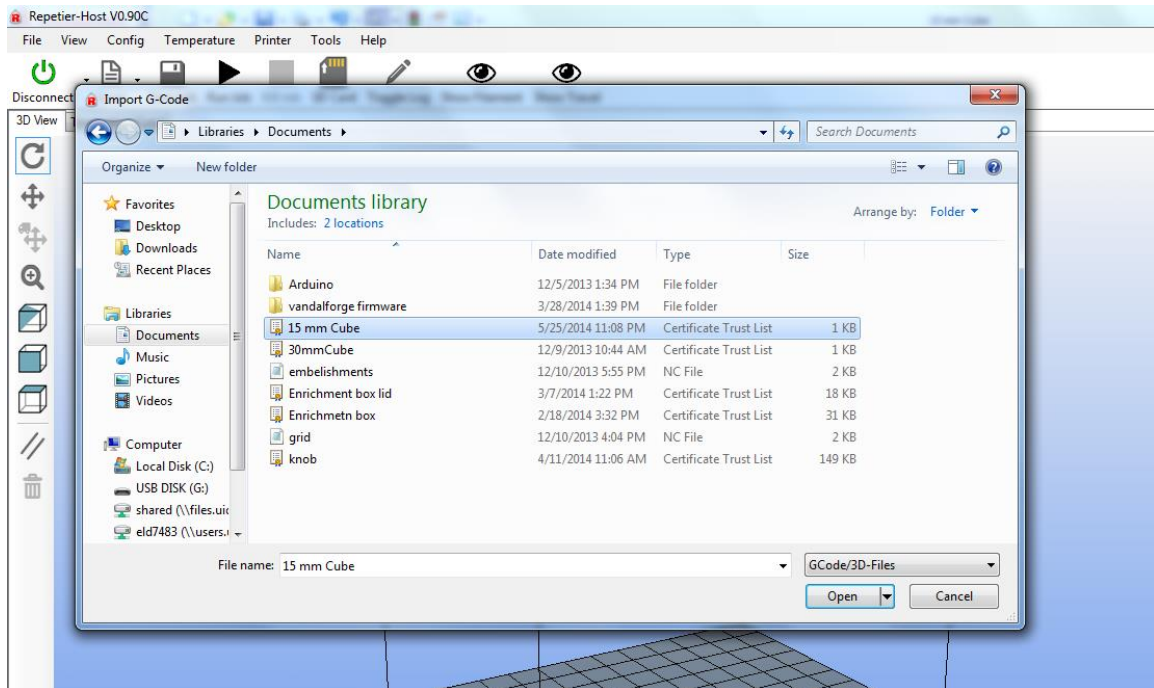


Figure 57. Selecting the part to print.

4. Use the part positioning window the set the position and scale of the part. The part positioning menu can be seen in figure 58.

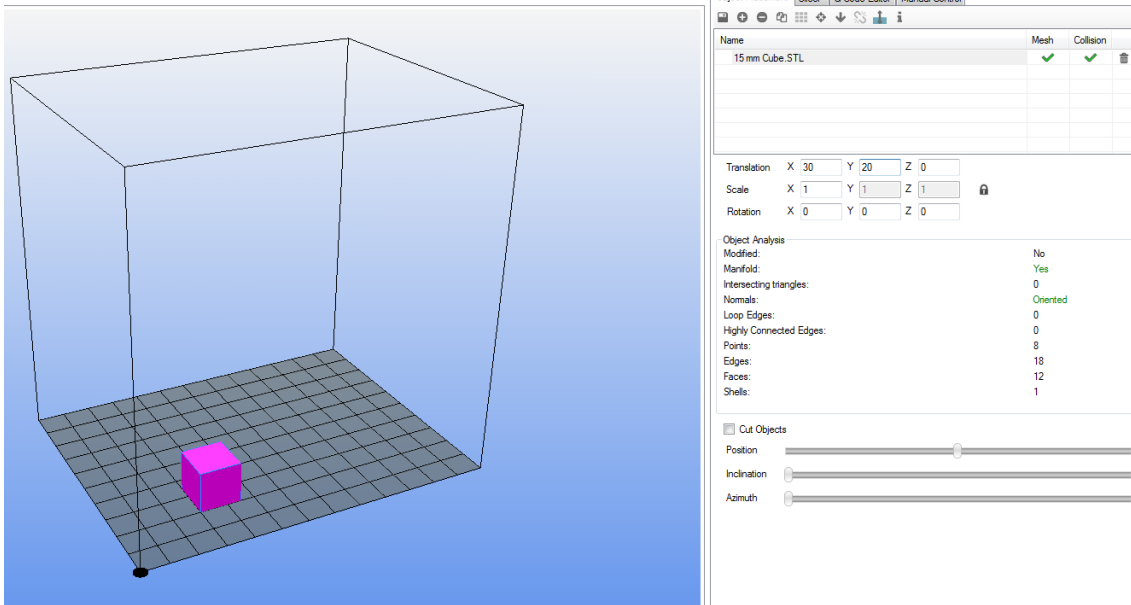


Figure 58. Positioning the part.

5. Switch to the slicing tab.
6. Verify that all the material and printer settings are correct for the print
7. Click on the slice button. The slicer menu can be seen in figure 59 below.

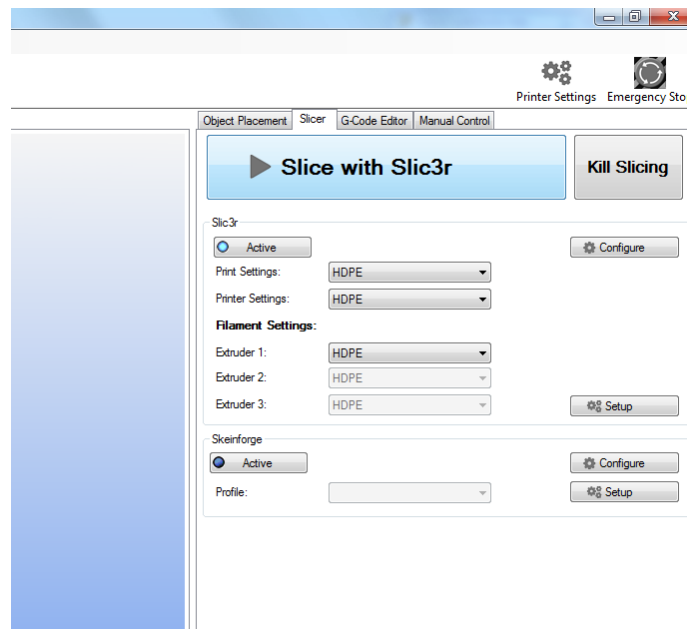


Figure 59. Slicing tab.

8. Wait for the program to finish slicing
9. Click on the G-code window
10. Look at the display window to see the tool paths that were created and verify that it looks correct. An example of this can be seen in figure 60 below.

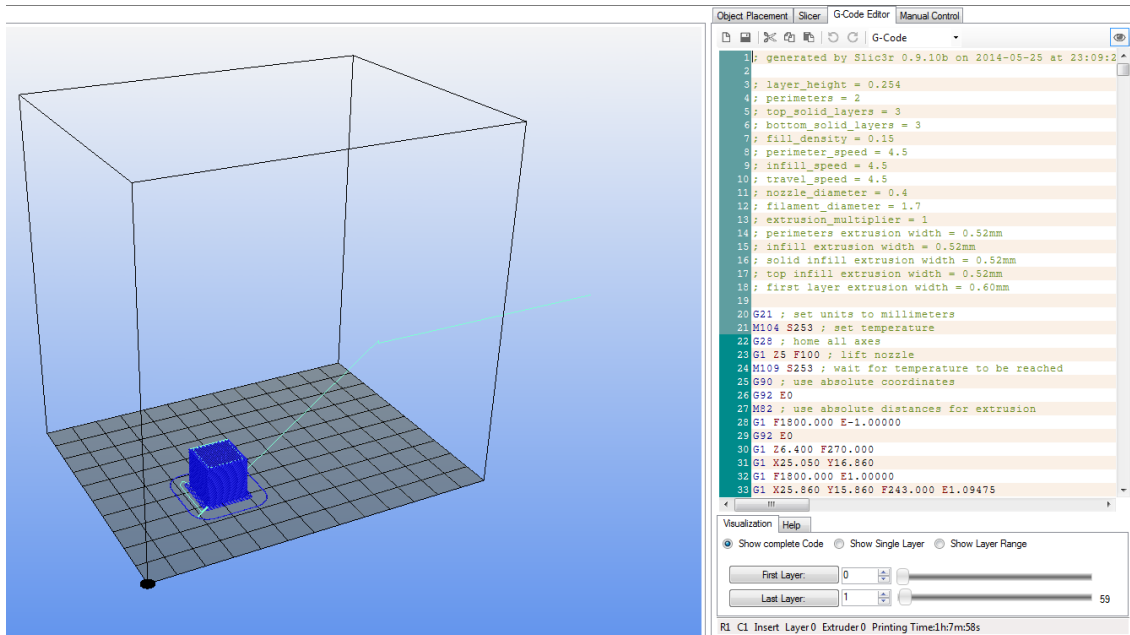


Figure 60. G-code window displaying code and toolpaths.

11. Click on the run button to begin the print. The prototyper should now home each axis and then go to the starting position of the print.
12. Watch the prototyper as it begins the print and it looks like it is going to crash into itself hit the reset button.
13. Look for signs of trouble as it starts printing such as the extruded plastic not sticking or the nozzle dragging on the print bed. An example of what a starting print looks like is in figure 61.

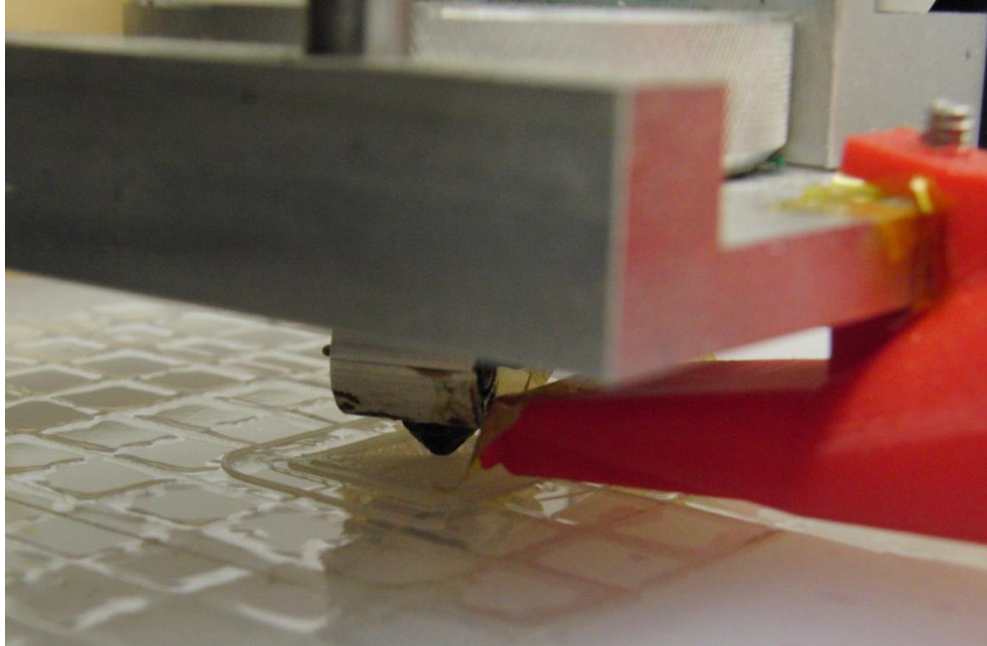


Figure 61. Print starting.

14. Check on the prototyper throughout the print to make sure that the extruder hasn't jammed or that there are not any other problems with the print.
15. Once the print is complete remove the part from the print bed.
16. Shutdown the machine if it's done being used.

5.3.3 Subtractive manufacturing

There are a number of ways the CNC milling capabilities can be used. The general process is to have a CAM program generate a G-code file then use Repetier Host send the G-code to the prototyper. For these instructions the program MakerCAM will be used. MakerCAM requires a vector image in the .SVG format to create tool paths. In this case an image of a 150mm X 100mm grid will be used. The vector image used was created using Inkscape an open source vector graphics program.

1. Access MakerCAM by going to <http://www.makercam.com/>

2. Make sure that the scale in MakerCAM by going to Edit -> Edit Preferences and set the import resolution to the correct setting like in figure 62.

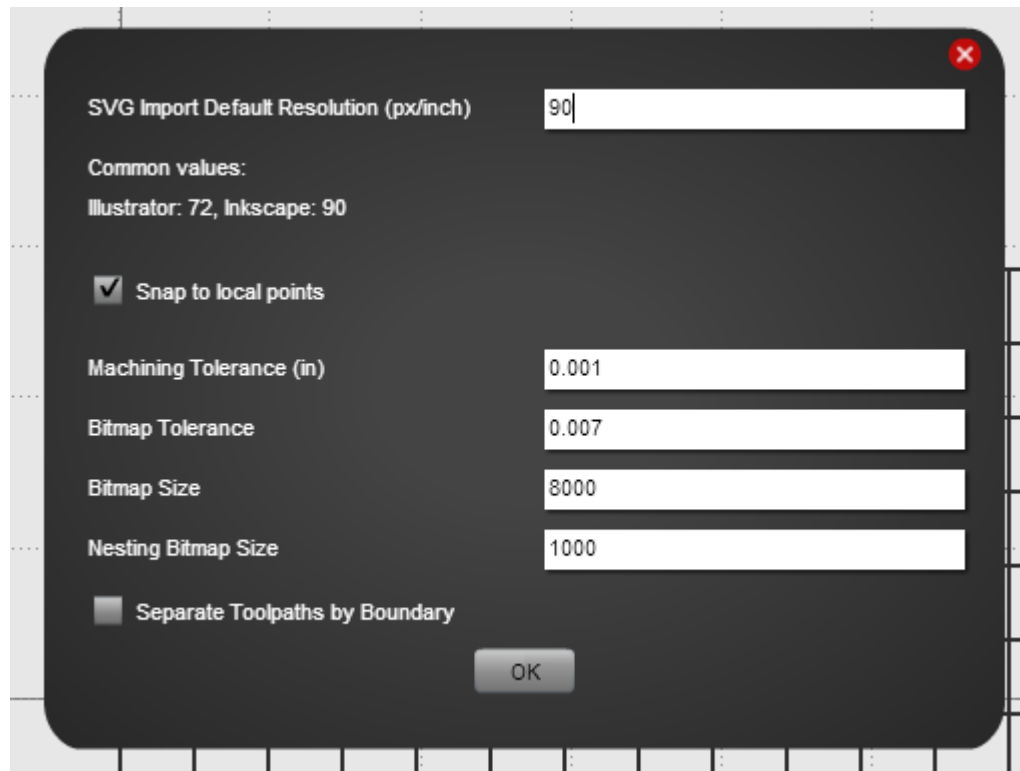


Figure 62. MakerCAM preference window.

3. Set MakerCAM to the appropriate length units like in figure 63.

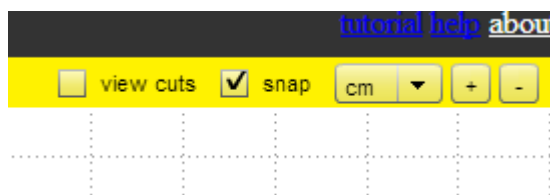


Figure 63. Setting units appropriately.

4. Click on File then Open SVG file
5. Browse to the file and click open. An example can be seen in figure 64.

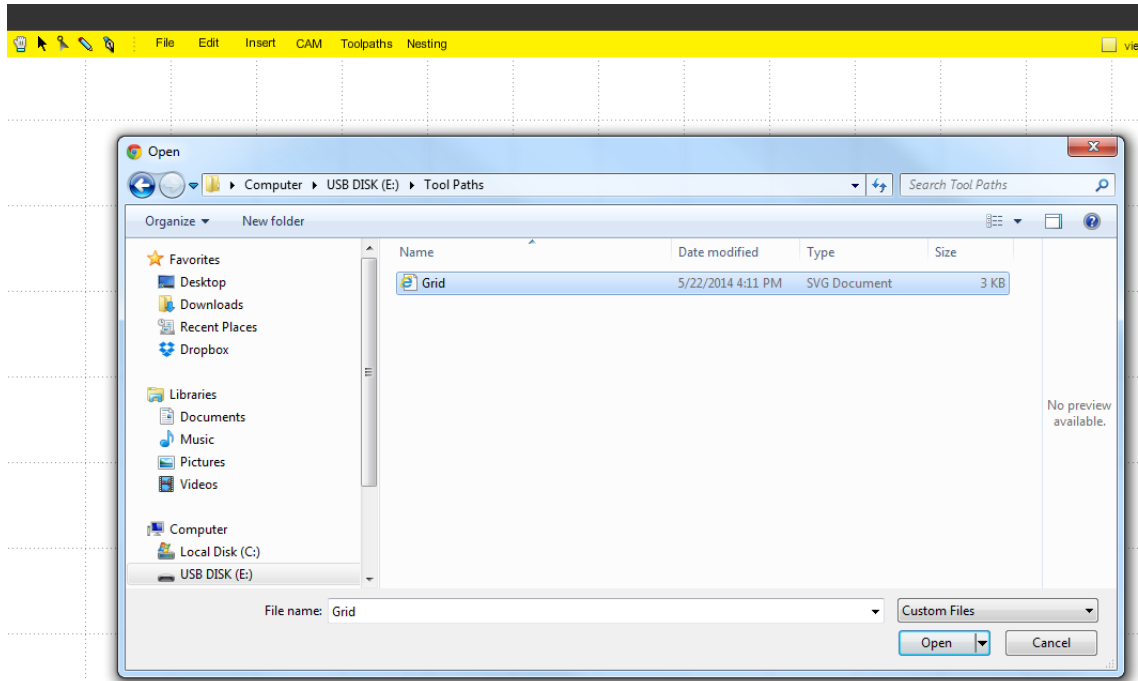


Figure 64. Selecting the desired file.

6. Move the image in the workspace if it is not in the correct position.
7. Select the desired path, as seen in figure 65.

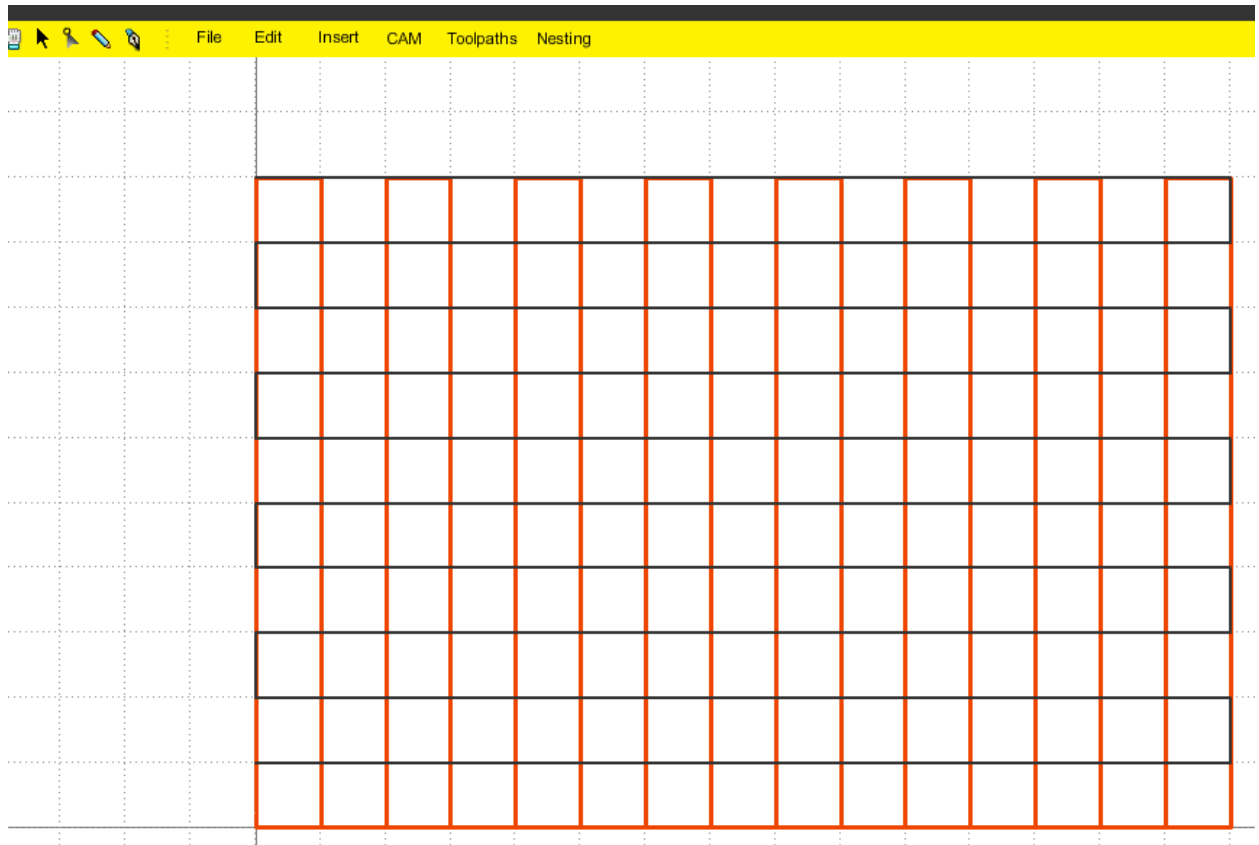


Figure 65. Selecting the path.

8. Click on CAM and select desired type of tool path like in figure 66.

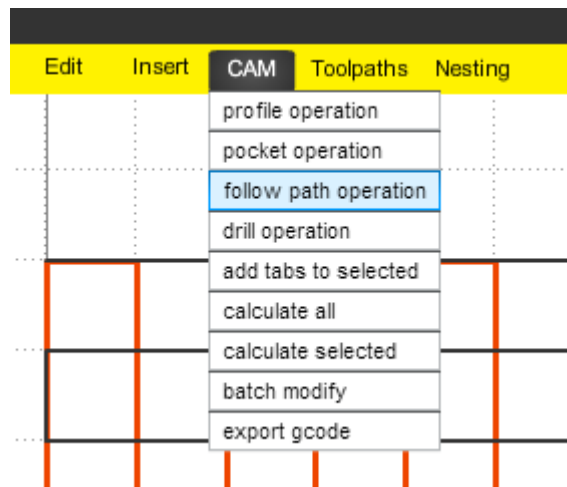
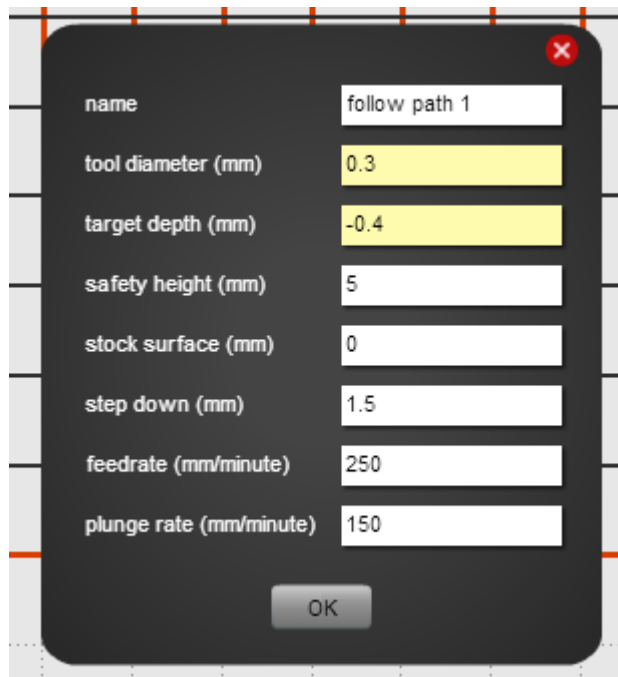


Figure 66. Creating the follow path operation.

9. Type the desired settings into the tool path dialog. The settings window can be seen in figure 67 below.



name	follow path 1
tool diameter (mm)	0.3
target depth (mm)	-0.4
safety height (mm)	5
stock surface (mm)	0
step down (mm)	1.5
feedrate (mm/minute)	250
plunge rate (mm/minute)	150

OK

Figure 67. Tool path settings window.

10. Repeat for the rest of the desired paths.
11. Click on CAM -> calculate all like in figure 68.

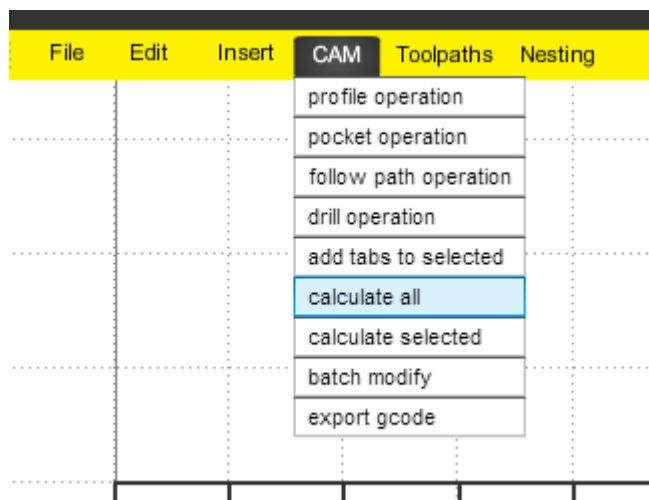


Figure 68. Calculating the tool path.

12. Click CAM -> export G-code to bring up the code export window.
13. Select the desired paths and click the Export Selected Toolpaths button. The toolpath export window can be seen in figure 69 below.



Figure 69. Exporting toolpaths.

14. Select where to save the file and click save as can be seen in figure 70.

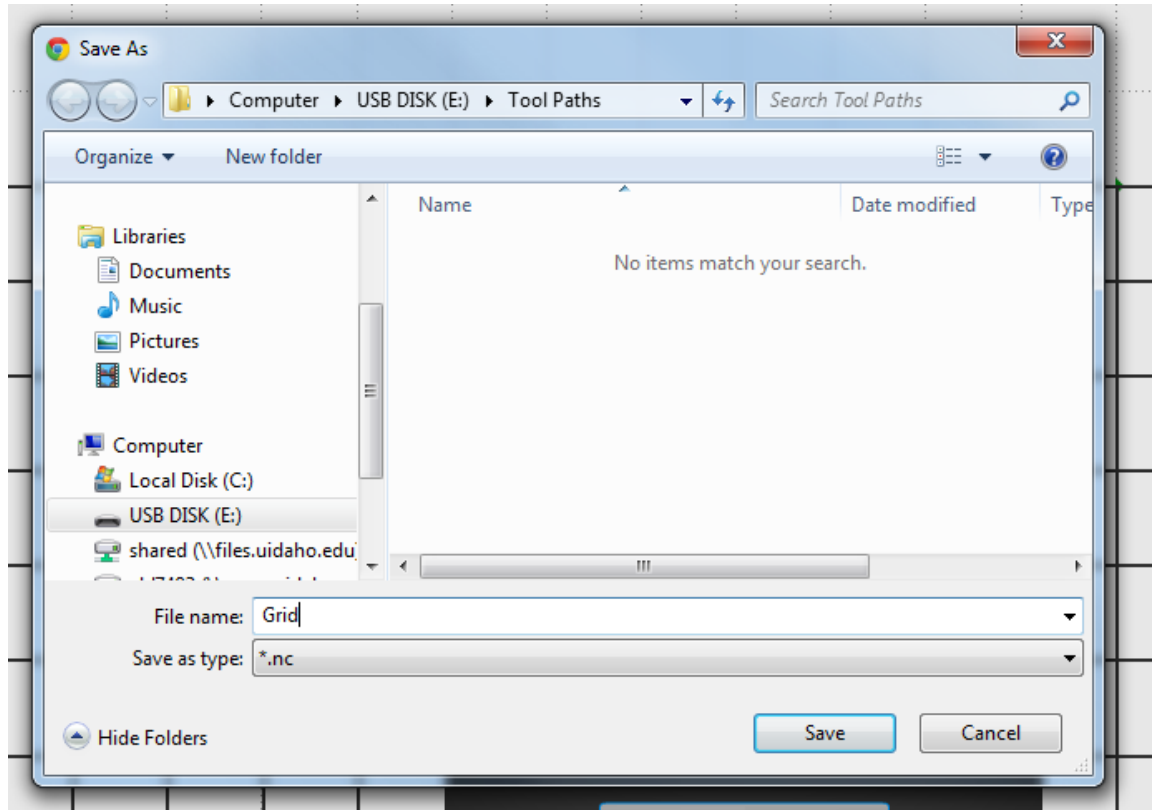


Figure 70. Saving the G-code file.

15. Set up the prototyper by switching it to milling mode and setting the tool height.
16. Open the G-code file in the G-code window of Repetier Host.
17. Setup the material to be cut. In this case it is the print bed itself.
18. Home each axis.
19. Start the spindle and set it to the desired speed.
20. Click the run button.
21. Watch the machine and be ready to hit the reset button if something goes wrong.
22. Use a vacuum to suck up chips and dust made by the milling. An example of this can be seen in figure 71.

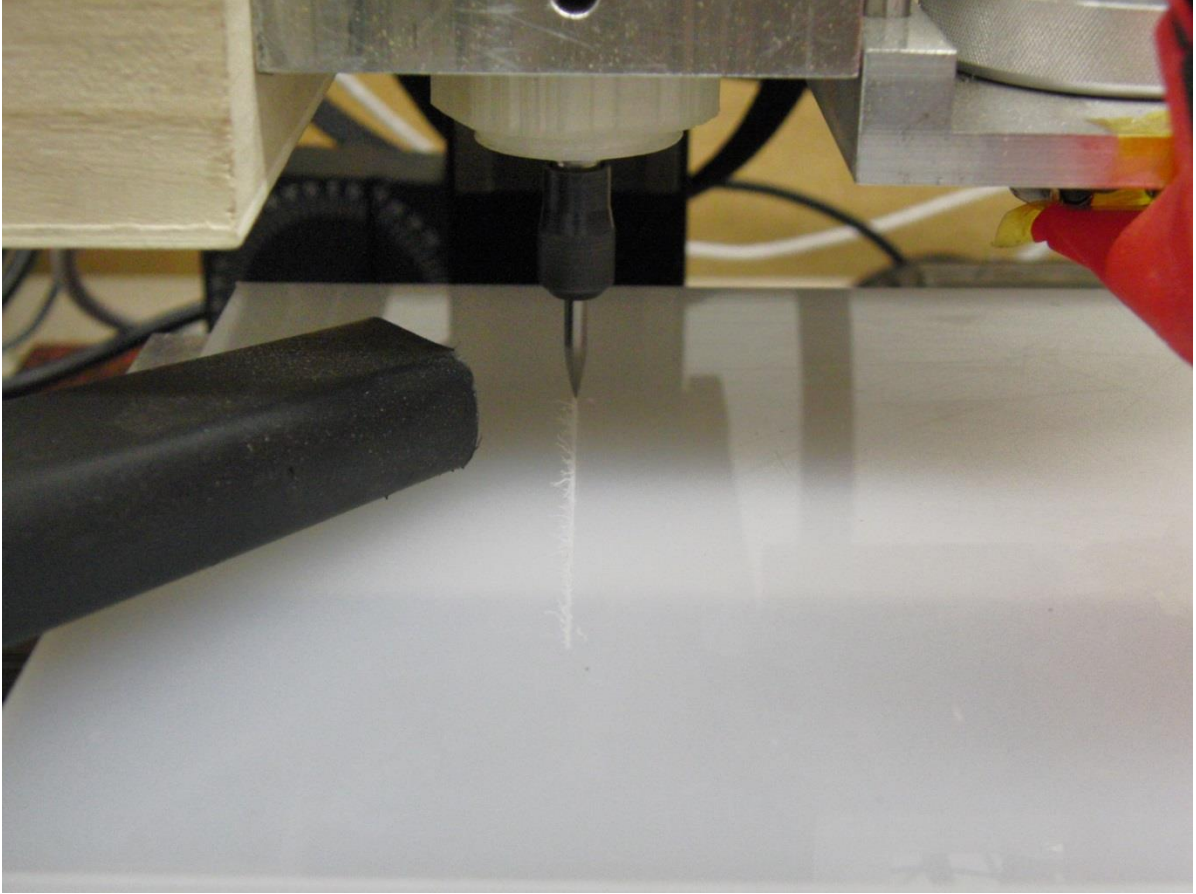


Figure 71. Following the mill with a vacuum.

23. Turn off the spindle when milling is complete
24. Shutdown the prototyper if it is done being used
25. Clean up.

Chapter 6. Designing Parts for 3D Printing

3D printing is a useful tool for creating prototype parts, both for checking fit and form and to produce functional parts. Throughout the project many parts were 3D printed from initial research to construction and testing many lessons were learned. There are a number of limitations to FDM printing but with planning their effects can be minimized. First the limitations need to be understood. Then how to deal with them can be assessed. For example if a part is being printed to test fit and form there is not much freedom to deal with effects of these limitations. If a part is a functional part that is to be 3D printed the limits of FDM can be minimized by designing the part with 3D printing in mind from the beginning.

The limitations of FDM are caused by a few main issues. Unsupported overhangs cause the biggest problems during the actual printing of the part. The resolution of the printer also limits what can be made. The layered nature of FDM parts makes them anisotropic and weakest in the direction normal to the print bed. Lastly the materials that lend themselves well to FDM are thermoplastic materials which are not as strong as common metals such as steel or aluminum.

Unsupported material has the largest effect on the print quality and how much if any cleanup work needs to be done to the part. A common way to deal with problem part features that result in unsupported material is to print a thin walled pattern of support material that can be removed after the print is complete. Most of the support material can be removed easily but it can leave small difficult to remove bits stuck to the surface of the part. For parts that are intended to be 3D printed at the very beginning of their design the need for support material

can be minimized or eliminated altogether. Even complicated parts can be printed with no support when designed with printing in mind, like the part seen in figure 72 below.

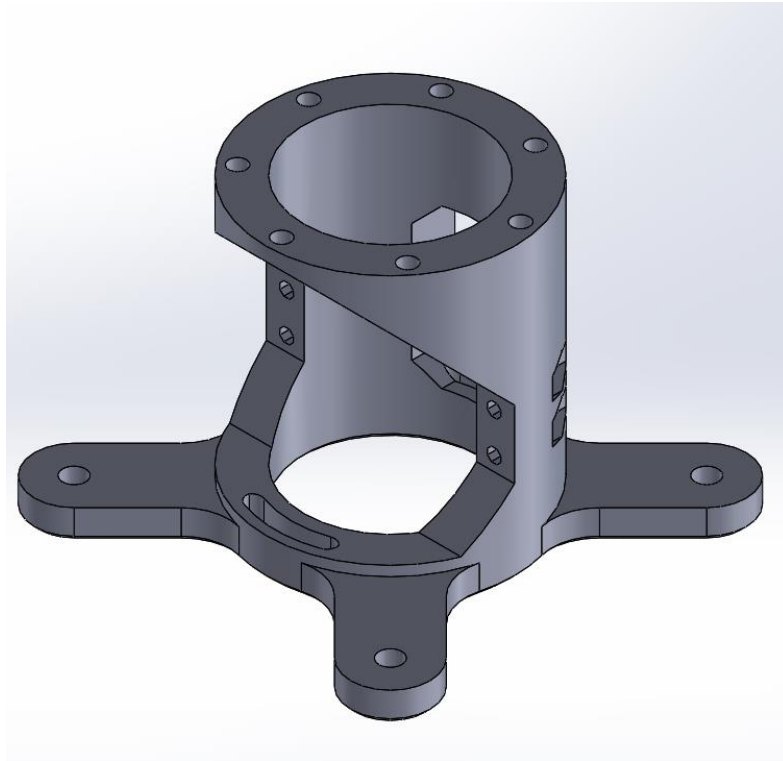


Figure 72. Example of a complex part that can be printed without support material. There are a few key types of part features that need to be understood in order to optimize a design for printing. These features are overhangs, bridges, and arches. Overhangs that flare outward at an angle from the print bed of 45 degrees or more can be printed without support. At an angle of 45 degrees or greater the outer perimeter of each layer is partially supported by the layer below it. This is highlighted in figure 73.

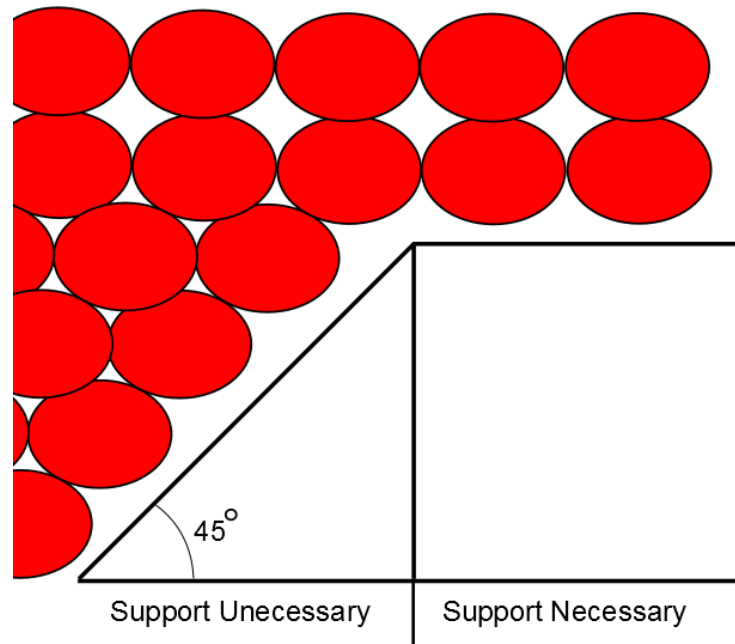


Figure 73. When an overhang needs support.

Parts can have lengths of unsupported material if it spans between two supported points. This feature is known as a bridge. Bridges can have problems with drooping material underneath if the span is too long. An example of a bridge feature can be seen in figure 74 below.



Figure 74. Bridging between two points.

Arches can sometimes suffer from drooping in the center. This is because in the center the angle is shallower than 45 degrees from horizontal. Horizontal holes in parts can be

improved in some cases by switched to being octagons instead of circles; this is most beneficial for small holes.

Resolution also affects what can be made. The smallest incremental step the machine can mover can have some impact but the biggest driver of resolution is the diameter of the print nozzle. Diameter of the nozzle determines the possible layer heights and the possible wall thicknesses. Layer height cannot be greater than the diameter and cannot be much less .1 mm. When designing parts with thin features the diameter becomes important. Thin walls work best if the thickness is a multiple of the nozzle diameter. Walls must at least be the width of the nozzle diameter and small widths that are not integer multiples of the diameter can cause problems. For example a wall that's 1.5 times the diameter would end up as just the diameter of the nozzle. Likewise a wall 2.5 times the diameter would have a gap between the walls making the part weaker.

How to attach the part being designed to other parts is another consideration. One solution is to use coarse threaded screws made for plastic in a hole in the part. For small bolts such as 4-40 or smaller, a regular bolt can be used in a hole slightly smaller than the major diameter of the thread. Both of these solutions thread directly into the plastic which is okay if they are not taken apart often or they will wear out quickly. A popular solution for connections is to design a part with a hex shaped recess that a metal nut can be put into. There are also a number metal thread inserts that could be used. Large coarse threads can be printed but they are only useful for light loads. Examples of these types of connections can be seen in figure 75.

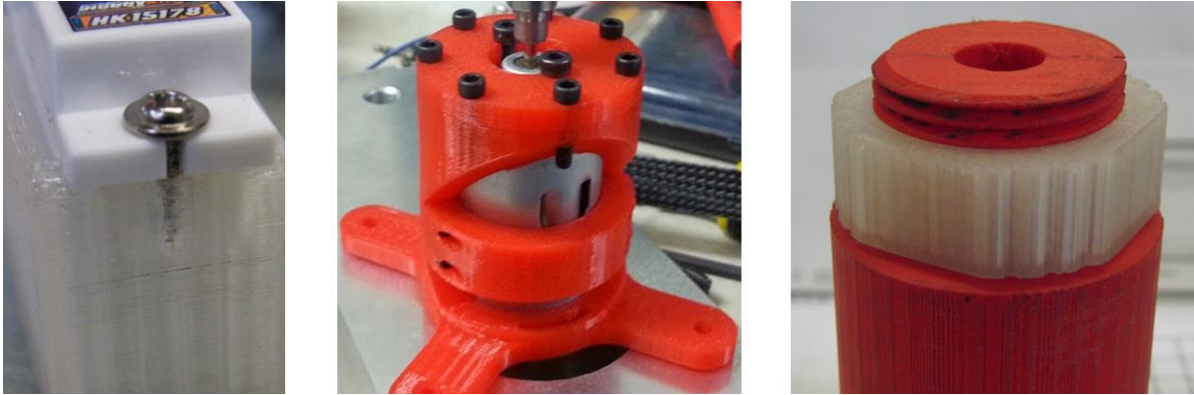


Figure 75. Coarse threaded screw, M3 bolts in plastic, and Large Printed threads

The layered nature of FDM parts makes them the weakest in the direction of the Z-axis. It also determine what part features are going to have the most problems in the printing process. This property makes picking the orientation that the part is printed in important. For some parts it comes down to what orientation will simply have the least problems.

With the limitations of the FDM in mind parts can be designed so that they can be printed with good results. For best results the part has to be designed from the very beginning with 3D printing in mind. The process start by picking the orientation of the part as it will affect features such as overhangs, bridges, arches, and horizontal holes. Orientation will also affect what direction the part is the strongest in. During the design process if the overhangs can be kept to 45 degrees or steeper and bridges can be kept from being too ling, then the part can be printed without support material. There is one major advantage to 3D printed parts. Complex geometry such as surfaces with many curves does not make the part much more difficult and costly to produce like it does with machined parts. With this in mind it makes designing parts many curves to reduce stress concentrations or for aesthetics. Using 3D printing many unique and useful parts can be made.

Chapter 7. Conclusions

Overall the system did show it was feasible to prototype parts from post-consumer HDPE. While demonstrating feasibility the advantages and drawbacks of the current prototyper system were highlighted. The system is currently divided into three machines in order to split up the major engineering challenges. Eventually if the system is to be simple enough for widespread use the process will need to be streamlined.

Material processing with the current shredder and filament extruder is time consuming and labor intensive. The shredder does work well but the preprocessing the milk jugs by cutting them up can take a while. Filament extrusion is one area where the current system can be greatly improved upon. While functional the system is not consistent enough for 1.75mm and it requires constant supervision while running to prevent malfunctions. HDPE is more flexible than PLA which causes feeding problems if the diameter is too small. If the filament extruder is ran keeping the maximum filament size small enough to feed through the print extruder. Then with the variation of filament diameter the minimum filament size will be small enough to buckle and cause jams. Buckling from undersized filament could be minimized through a couple changes. A closed loop control system for controlling the diameter or simply going to the larger 3mm filament size. Making the system easy enough to use in a classroom setting is possible but there is considerable work left to simplify the system.

The prototyper is able to use both additive and subtractive manufacturing to some extent. 3D printing is possible in PLA and HDPE. Several test pieces were successfully printed using

HDPE proving its feasibility. Figure 76 below shows some of the test pieces printed with HDPE.

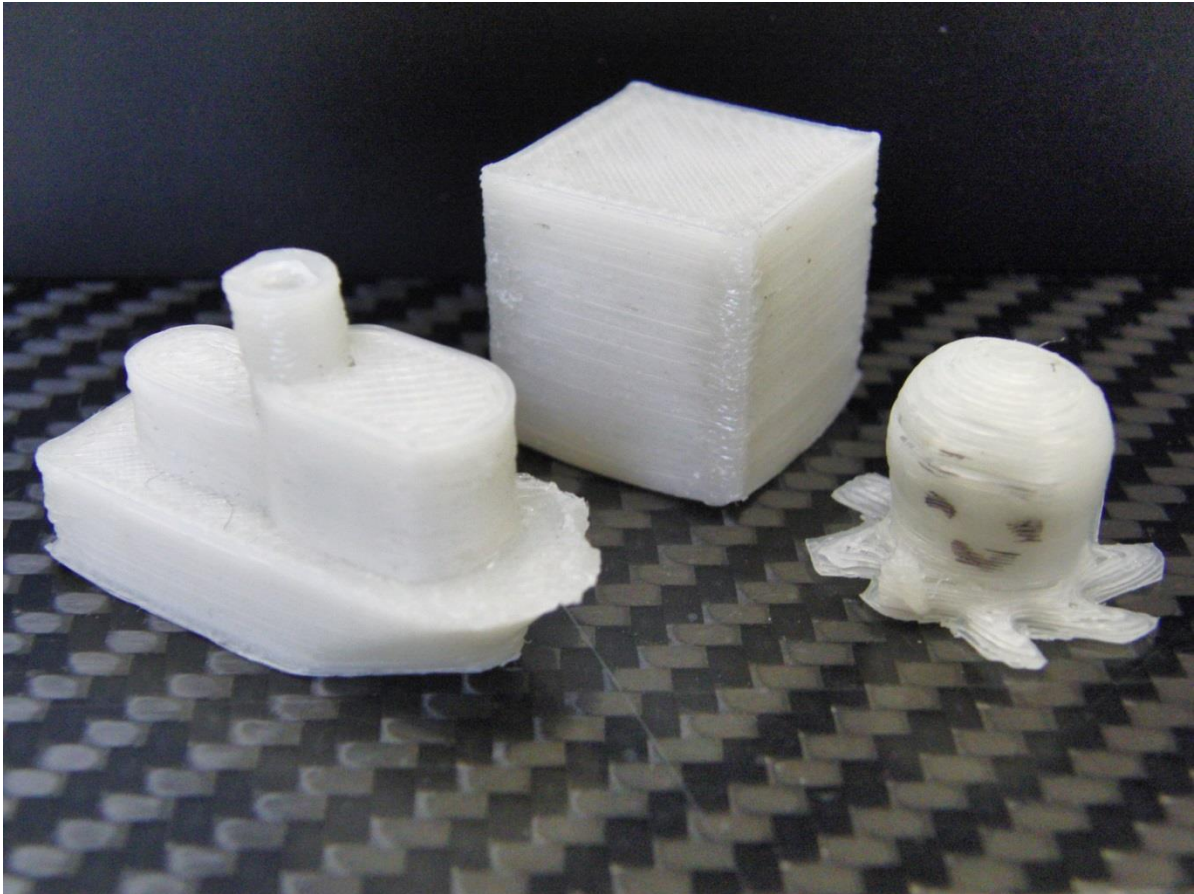


Figure 76. HDPE 3D printed test pieces, a tugboat, a cube, and an octopus.

One of the significant challenges to printing with HDPE is keeping it adhered to the print bed. This was overcome by learning that HDPE will bond to everyday clear packaging tape. Covering the print bed with the tape helps keep the parts in place during printing. When it comes to 3D printing the system does have one major drawback, its speed. It is fairly slow for a 3D printer due to its fine pitched lead screw system. This slow speed is a fairly big hindrance to wide spread use. The prototyper was able to use its CNC milling components to a limited extent. For RepRap based systems the CAM software options are mostly limited to

2D routing. More work would need to be done on the software tools to make it more capable.

The system is not currently ready for use in an educational environment. With as labor intensive as the material processing is it may not be seen as a worthwhile system. If it ends up being seen as just another burden on teachers it won't be successful in expanding the use of rapid prototyping in education. Solving the engineering challenges are foundational in making it possible but considerable work will need to be done in how integrate such a system into the educational environment. One way to deal with the material processing would be to incorporate it into lesson about recycling. It could demonstrate how plastics can be recycled. Use of the prototyper itself could be incorporated into projects involving manufacturing and the engineering process. As work progresses on ultra affordable rapid prototyping thought need to go into how to best integrate it into the classroom environment.

The project explored how to reduce the cost of rapid prototyping through the used post-consumer HDPE from sources like milk jugs. Several challenges had to be overcome such as how convert empty milk jugs to a readily usable form, how to build a system capable of multiple manufacturing methods, how to keep HDPE attached to the print bed, and others. This research was undertaken for part of a master's degree in mechanical engineering and to that end, I accomplished the following.

- Designed and built experimental prototyper system that
 - combined additive and subtractive prototyping
 - could use recycled HDPE.
- Made advancements in 3D printing with HDPE.

- Outlined best practices for designing parts for 3D printing.
- Identified potential avenues for further research in reducing the cost operating a 3D printer.

Chapter 8. Future Work

After exploring the current system and manufacturing methods conclusions can be drawn about suggested paths forward for research. Each part of the process from milk jug to part could benefit from further work to refine the process. Processing HDPE from milk jugs to filament would benefit from reducing the required labor and improving filament consistency. The prototyper could use a revision focusing on improving speed of the XY platform and refining the tool head. Along with hardware improvements there are significant benefits that could be gained from improving the user process and software tool chain used to make parts.

The process of converting post-consumer HDPE has a few areas where future work would be beneficial. Improvements to the shredding machine could be made in order to make it more effective. The power could be increased so that it could process more pieces of plastic at a time. A more effective shredding mechanism could be explored so that plastic only has to be passed through the machine once. Eventually it would be good if the only pre-processing of the milk jugs was washing and removing the label. Overall the current shredding machine is fairly affective so improvements to the shredding system are of low priority. Improving the filament extrusion system is a more pressing issue. Since the project began there has been progress in the hobbyist community in creating filament extrusion systems, and now there machines available. Exploring one of these systems such as the Filastruder or Filabot could prove to be useful as it could provide an off the shelf solution. If further work on a custom system is to be done there are a number of improvements that could be made. First would be a more refined electrical system. Improvements to the electrical system would include speed and temperatures controls and displays so that the

machine could be operated independent of a computer. A closed loop control system monitoring filament diameter would be a valuable improvement. Startup time of the system could be improved with a more powerful heater system. There are also improvements that could be made to the mechanical part of the filament extruder. A revision of the drive system reviewing the drive motor and speed reduction could produce a more compact and reliable solution. The overall length of the extrusion system can probably reduce allowing for the use of a shorter auger bit and less material. The most beneficial project would be a system with feedback control to draw filament from the machine to keep it a consistent diameter.

There are many aspects of the prototyper where future work could prove useful. One question that will significantly change the direction taken is whether or not the prototyper system should mix both additive and subtractive capabilities. A mixed manufacturing method machine is possible but it comes at a higher system cost and greater complexity. Basing the system solely on using a 3D printer and material processing system would reduce complexity but sacrifice flexibility of the types of parts it can make. Assuming a multi-method machine there are several areas where a second generation of the current system could be an improvement. The current speed of X and Y translation is holding the machine back in terms of being useful for everyday use. Coarser pitch lead screws such as fast travel acme lead screws could increase speed considerably although it would result in an increased system cost. The tool head system could go through a refinement to improve the overall design. Currently the prototyper's electronics are split into two systems the printer control box and tool head control box. Condensing the electronics into a single enclosure would reduce system complexity. The tools themselves could use improvement. A more powerful

motor with precise speed control mounted in a rigid mount would be useful. Quicker and more repeatable tool switching would make combining manufacturing methods easier. The long distance between the filament drive and hot end causes feeding problems so a redesign of the printer extruder could be done.

One attractive direction for future work is going to a 3D printing only system. This approach has the benefit of being able to largely use commercially available systems. Using a RepRap printer with an all metal hot end and polypropylene tape, such as clear packing tape, could be used to print with HDPE filament. Filament could be produced using one of the commercially available filament extruders such as a Filastruder that have become available. It would be beneficial to switch from 1.75mm to a 3mm system as it would help alleviate feeding problems from undersized filament buckling. The current design for the shredding machine could be used as is since it has performed satisfactorily.

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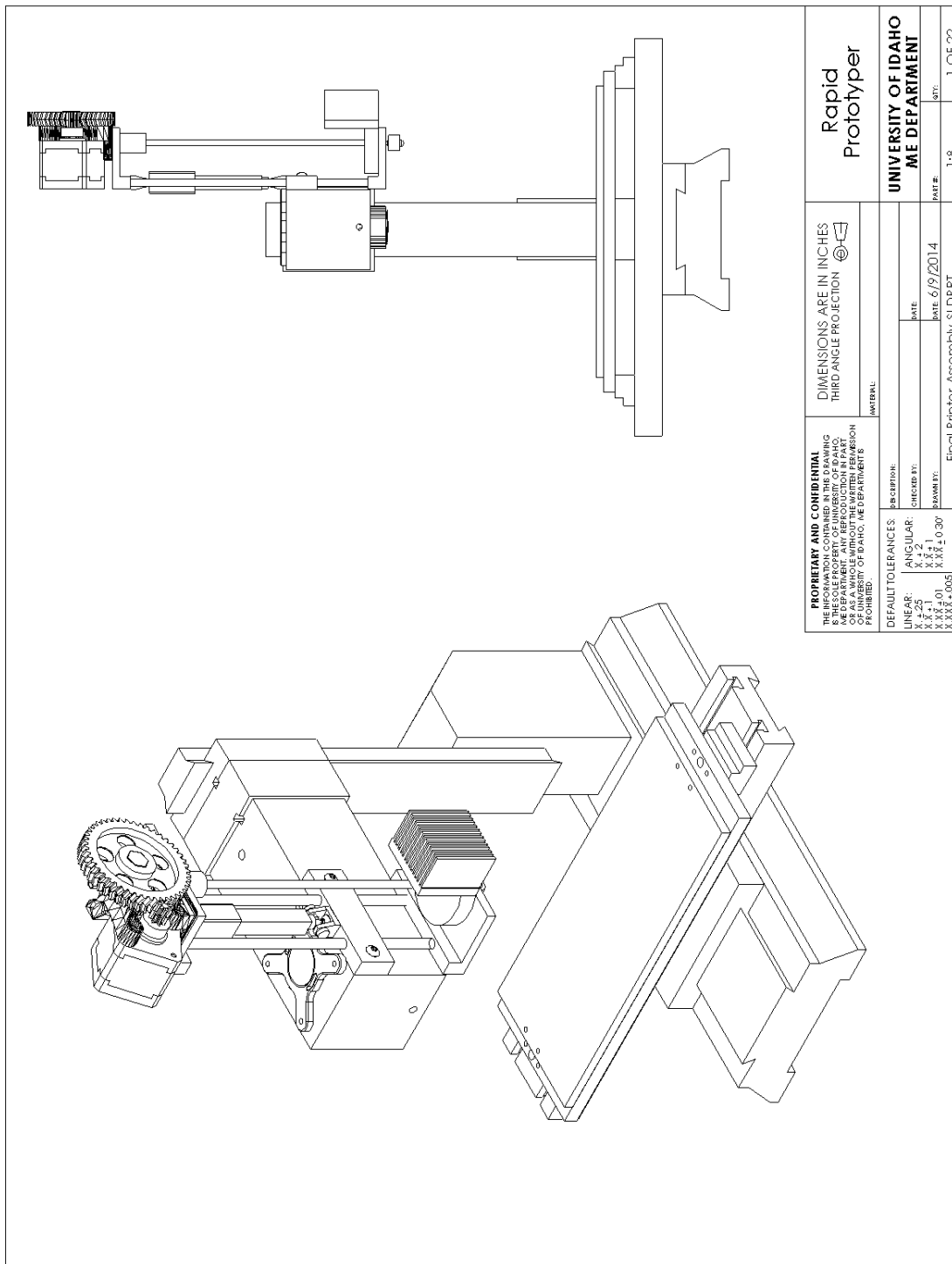
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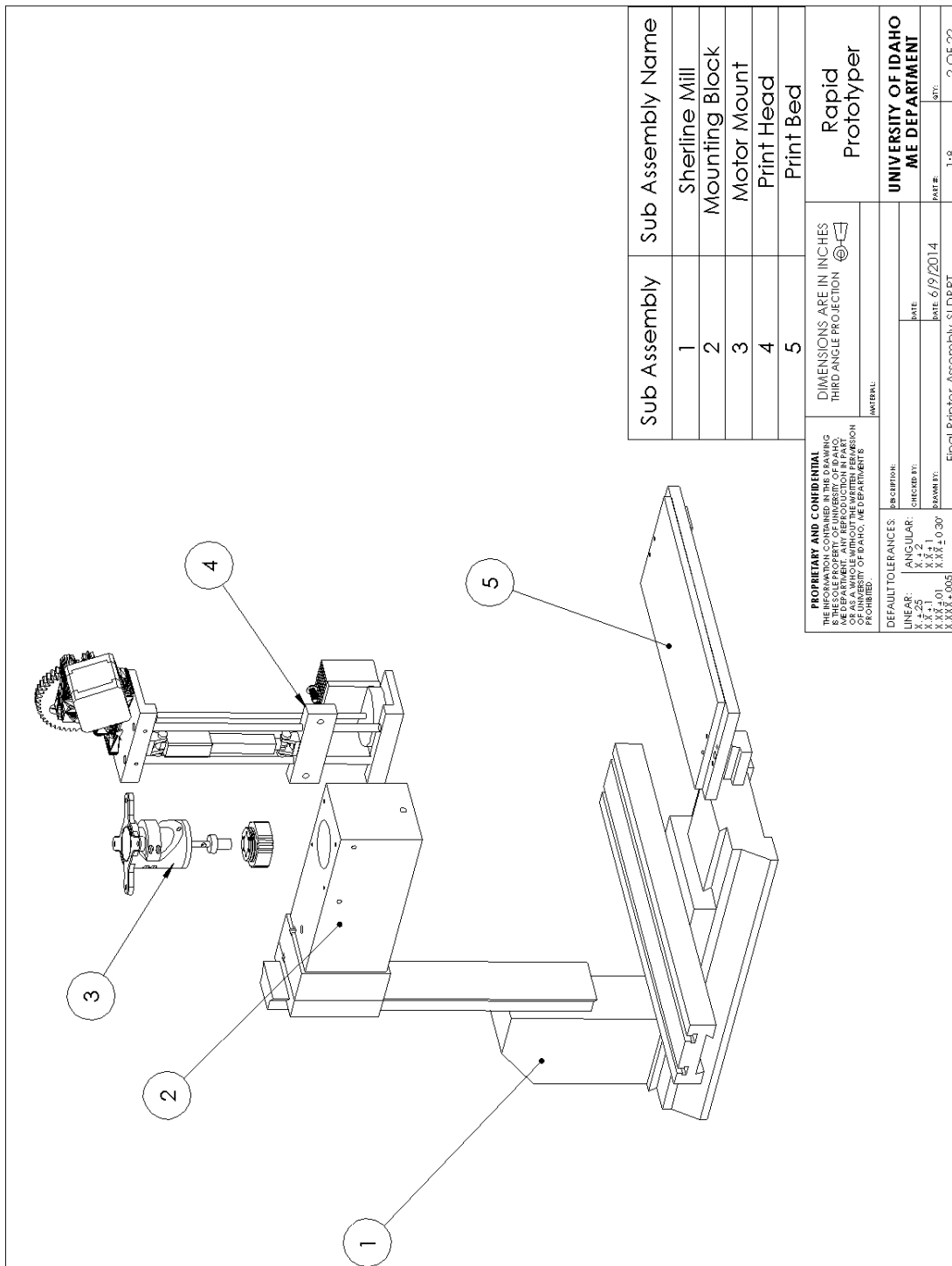
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Appendix I

Prototyper Drawing Package

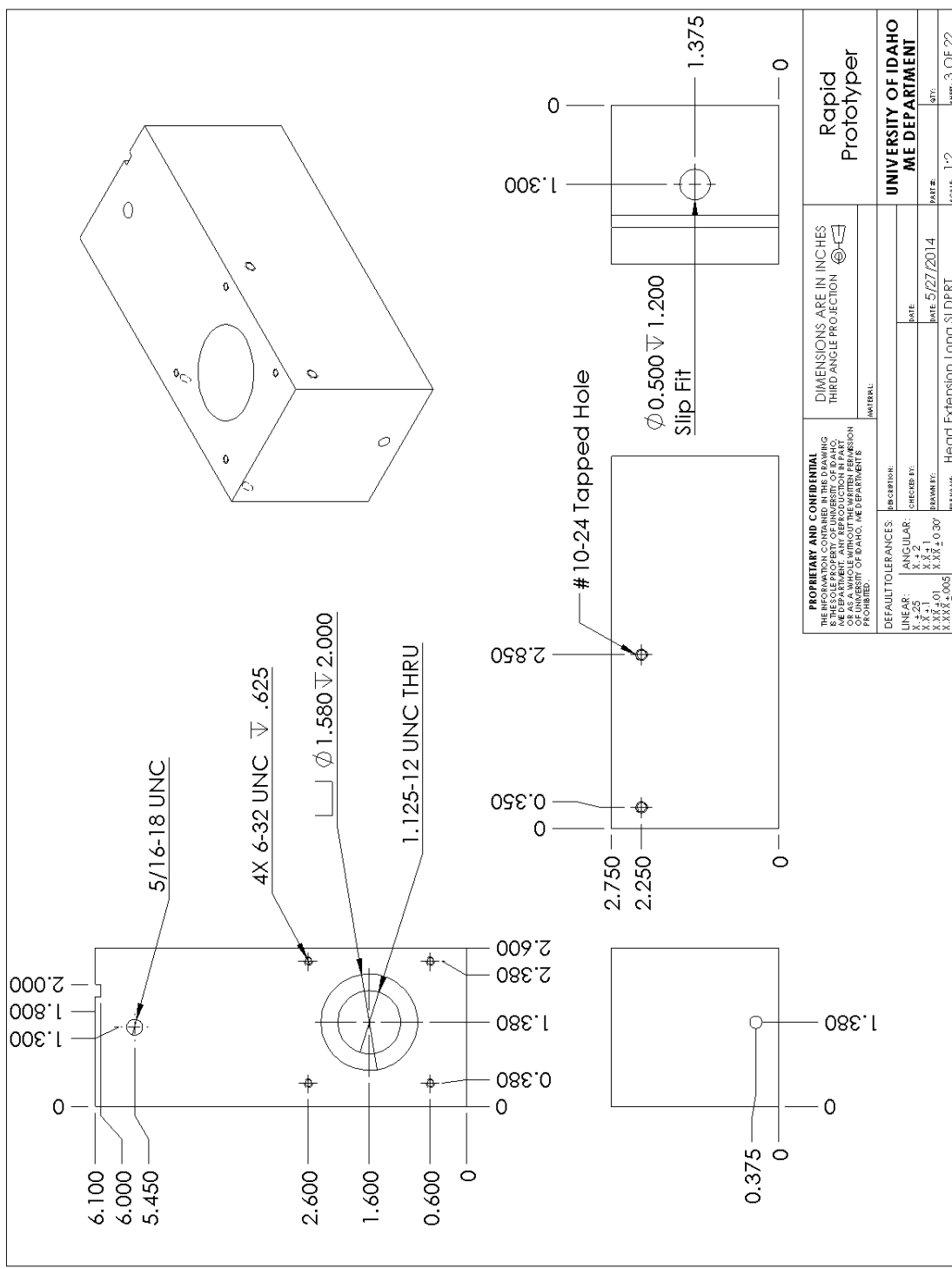


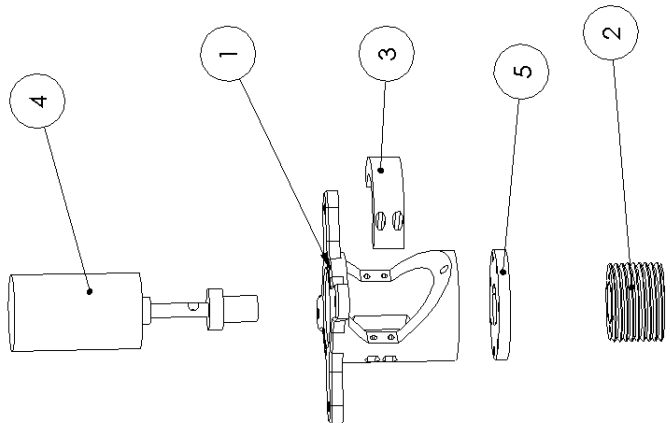
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Sub Assembly	Sub Assembly Name
1	Sherline Mill
2	Mounting Block
3	Motor Mount
4	Print Head
5	Print Bed

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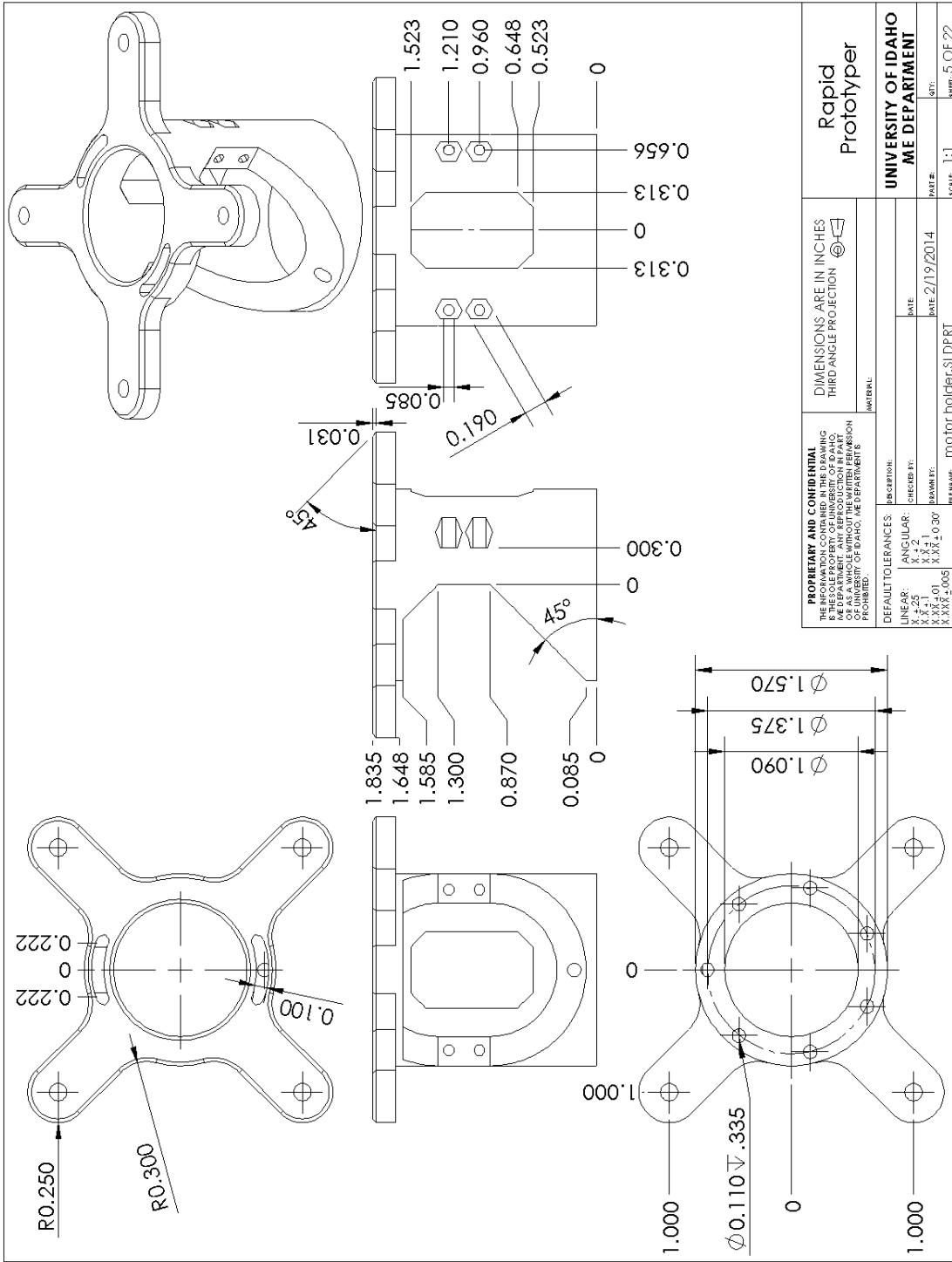


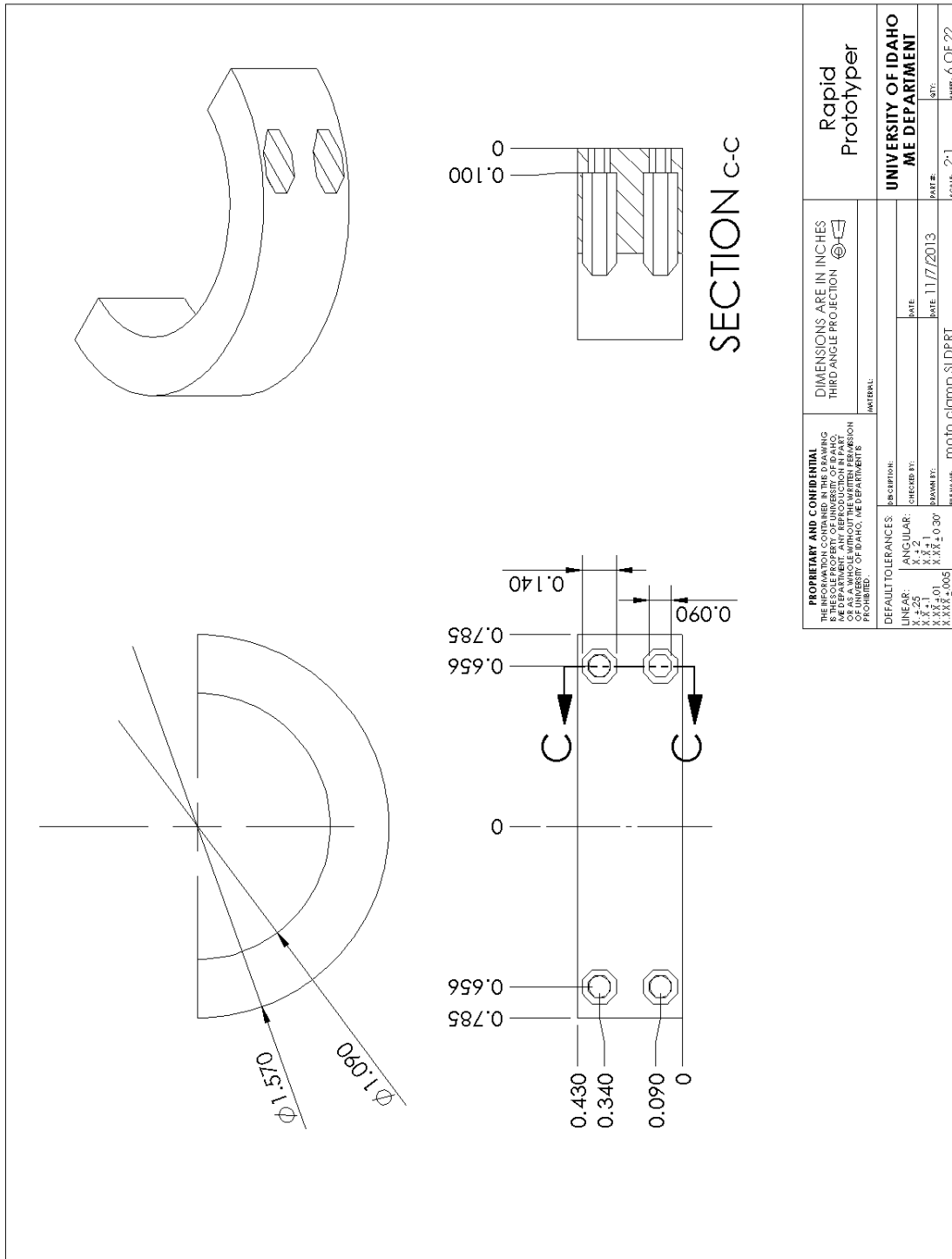


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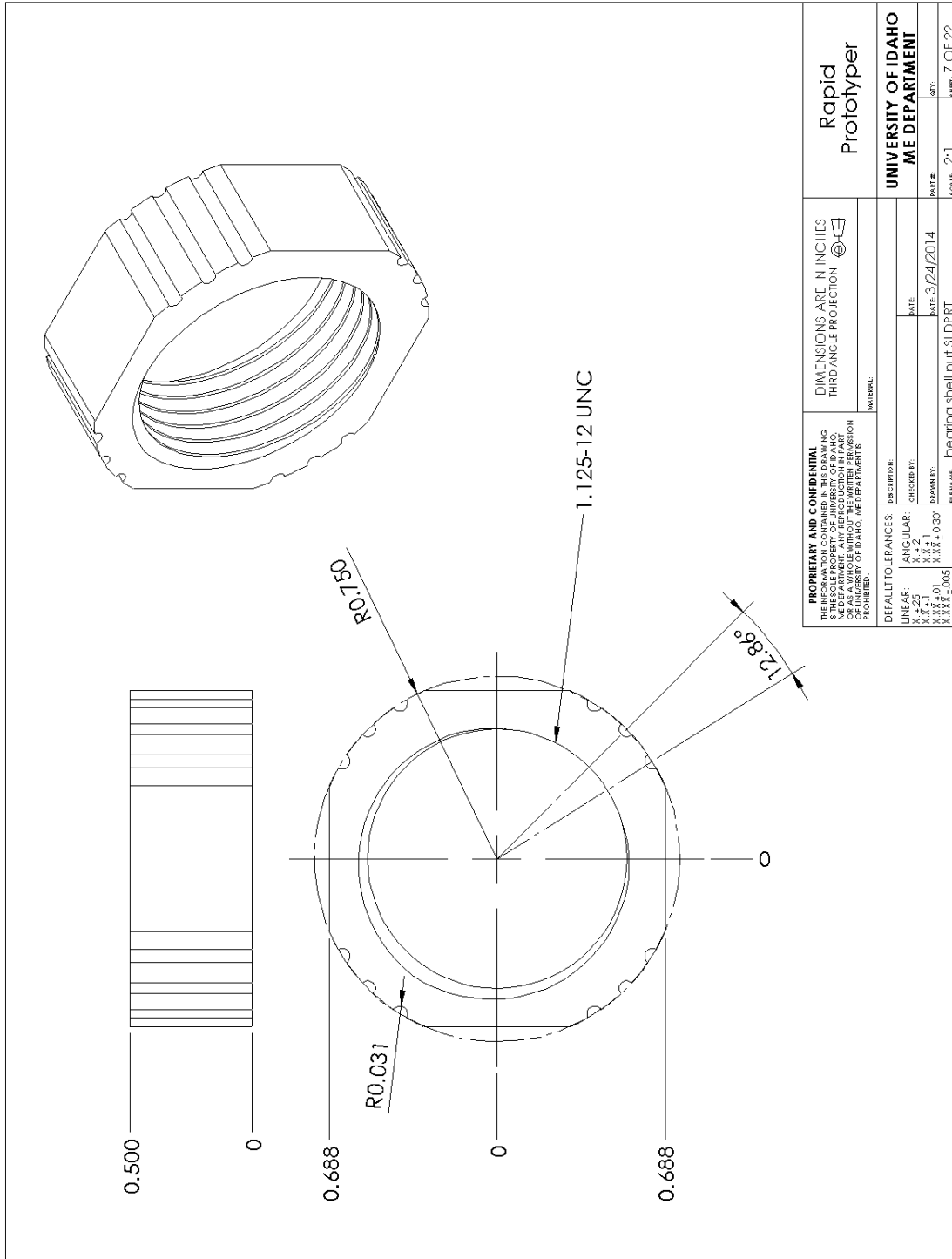
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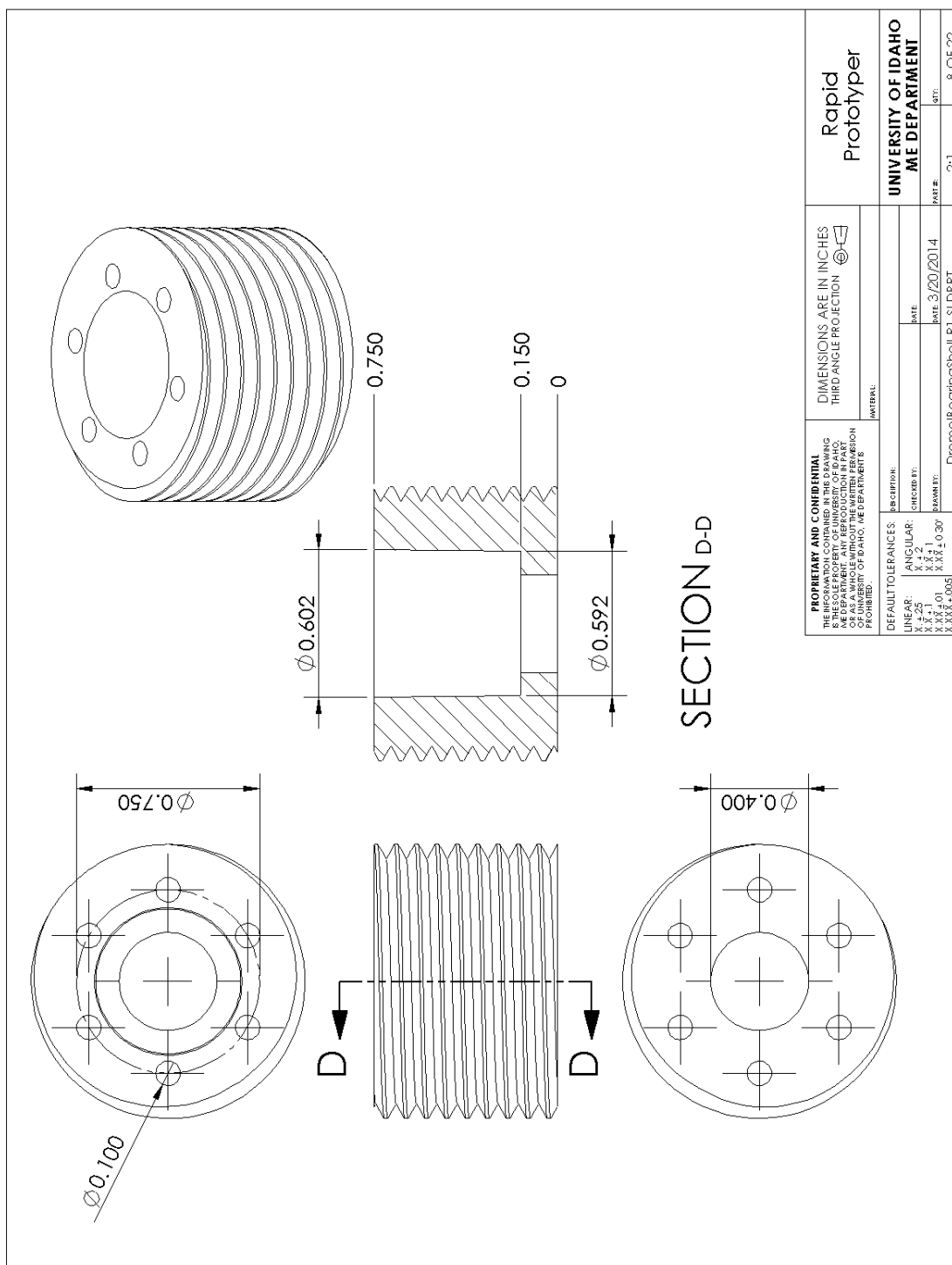
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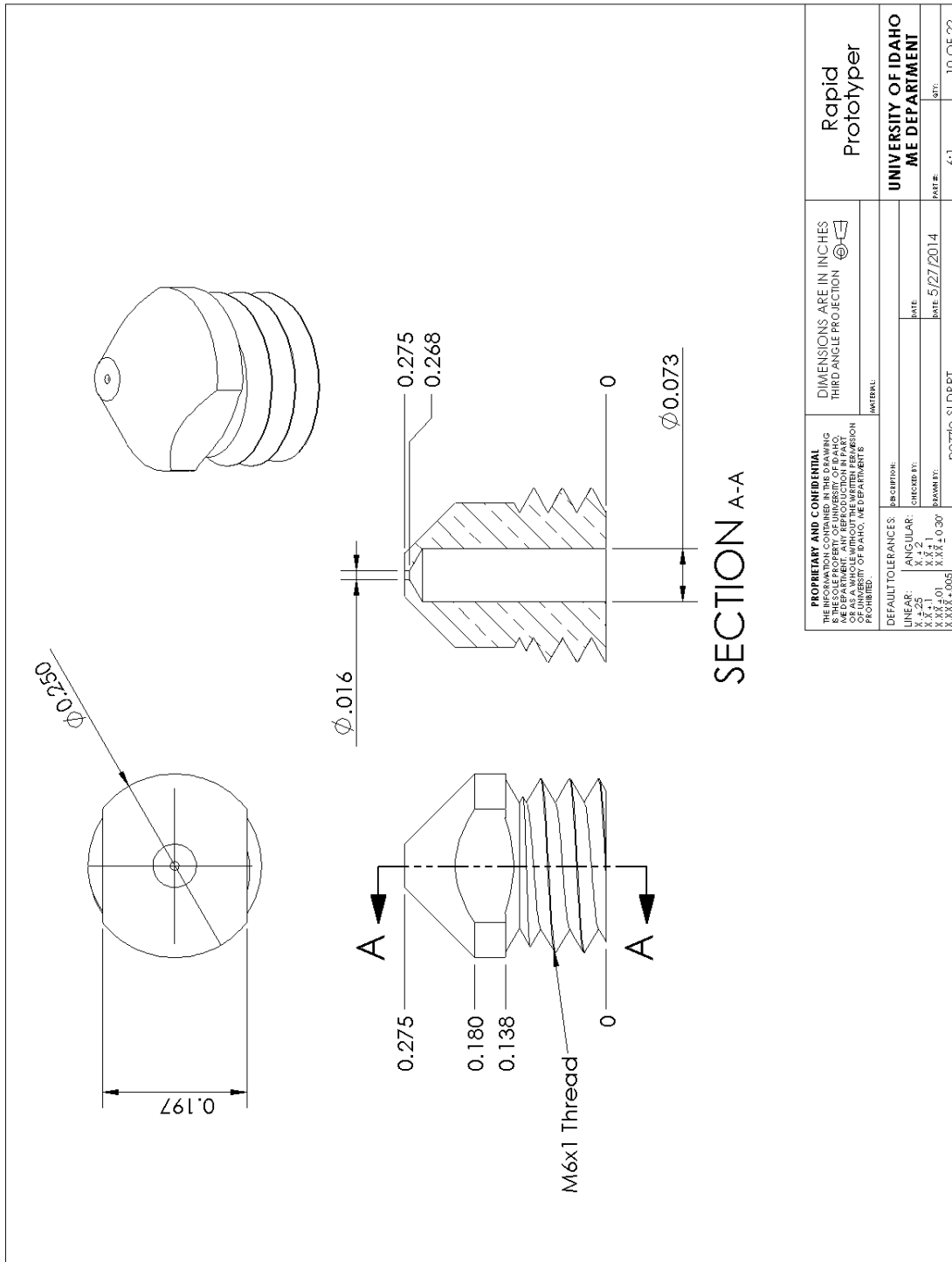
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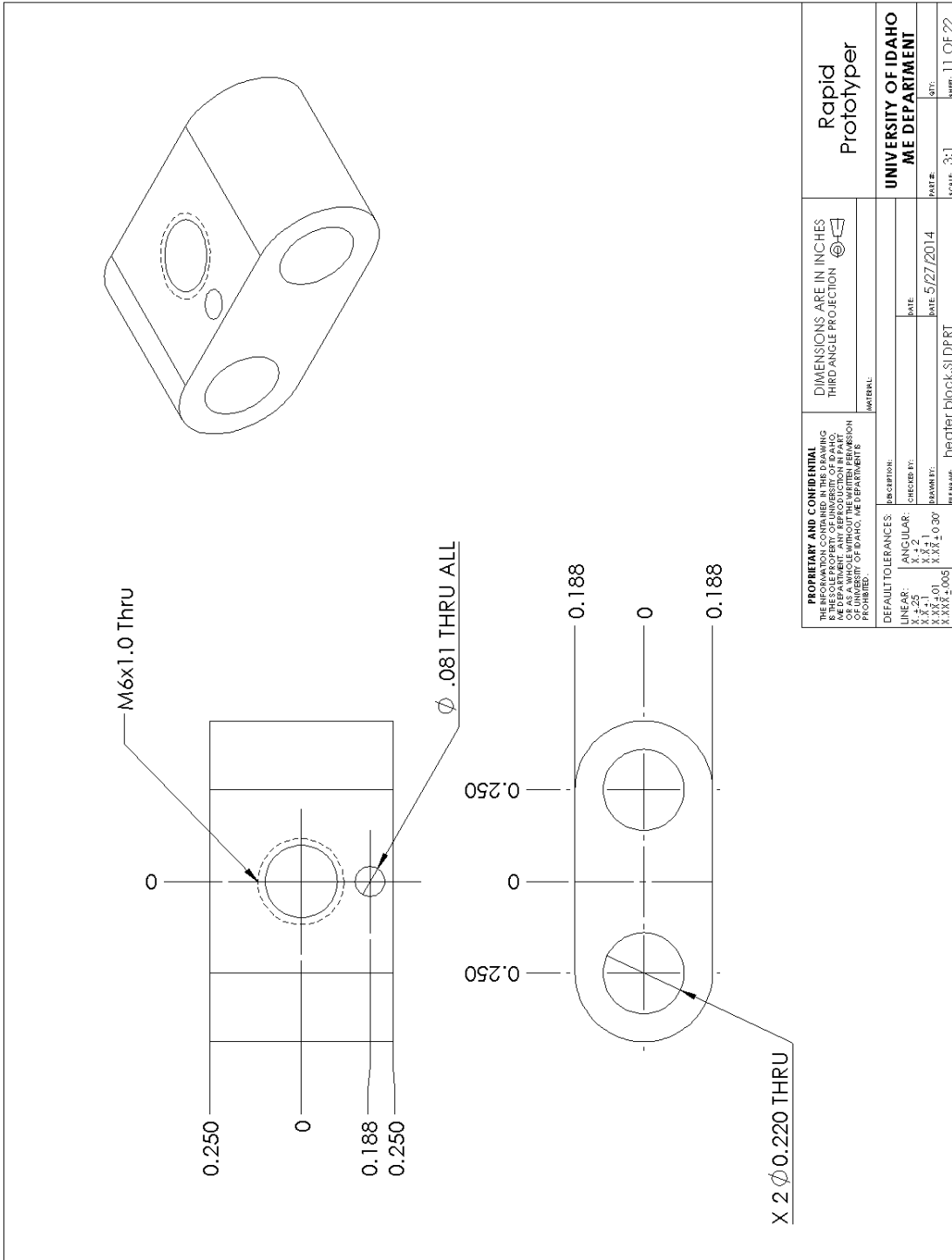
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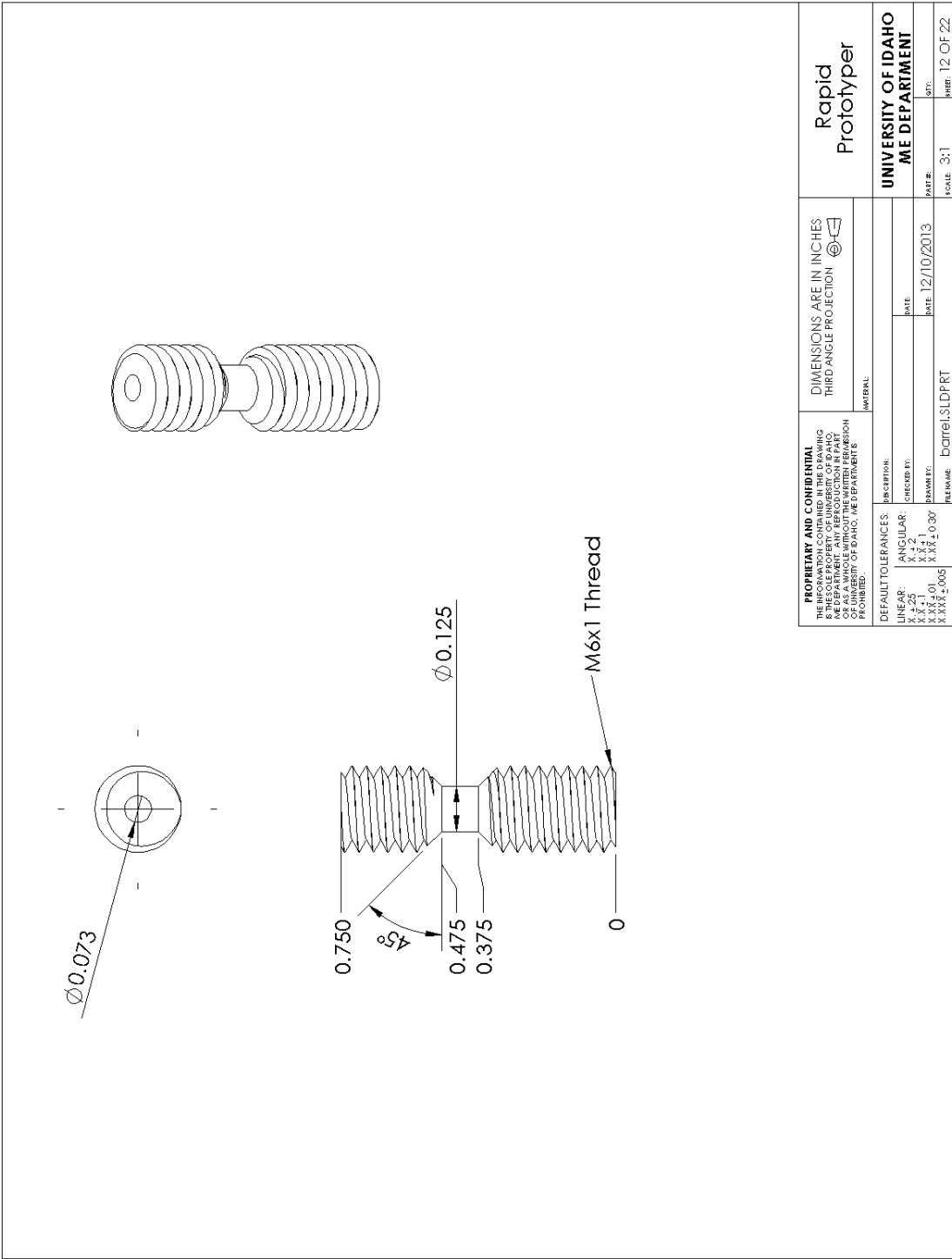
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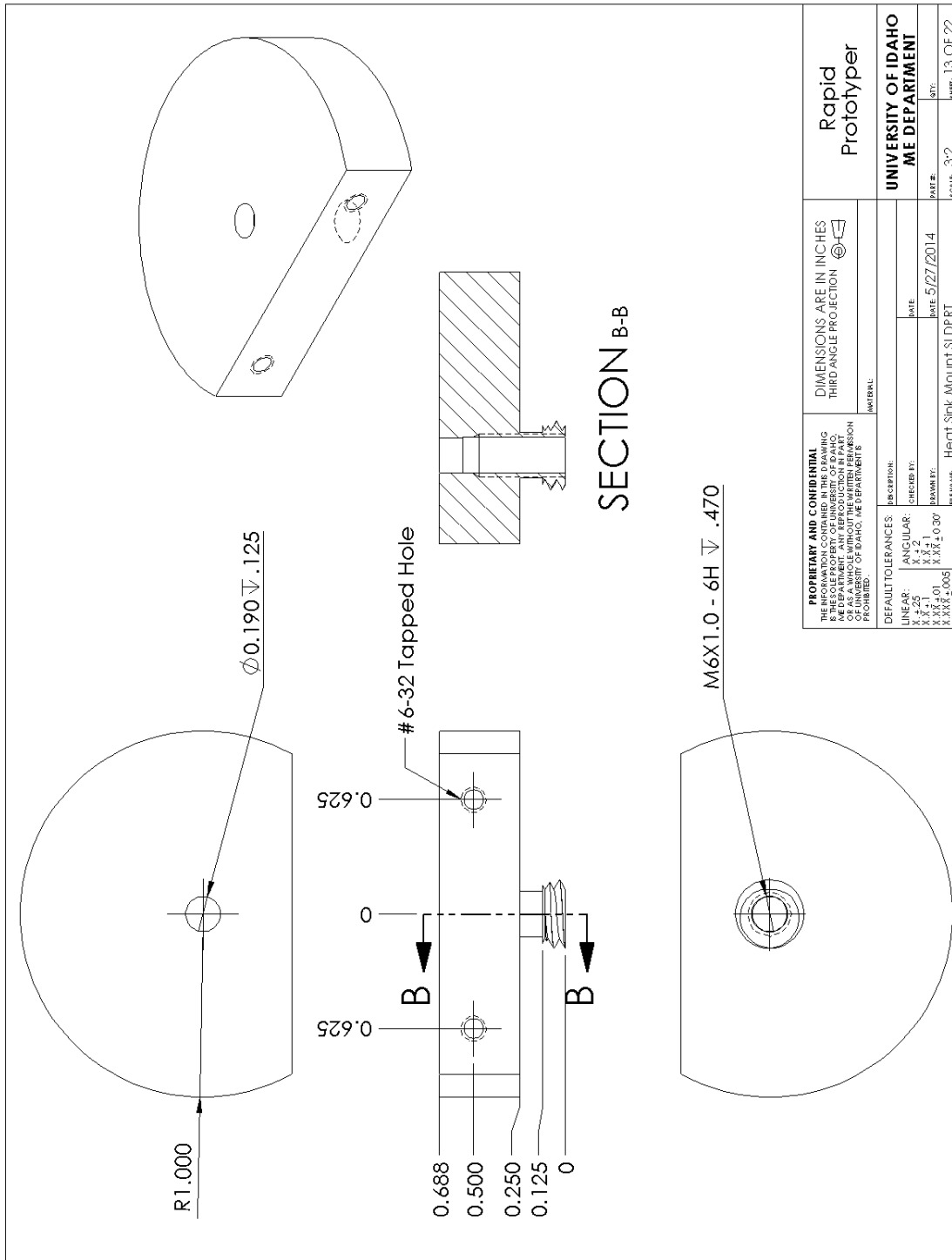
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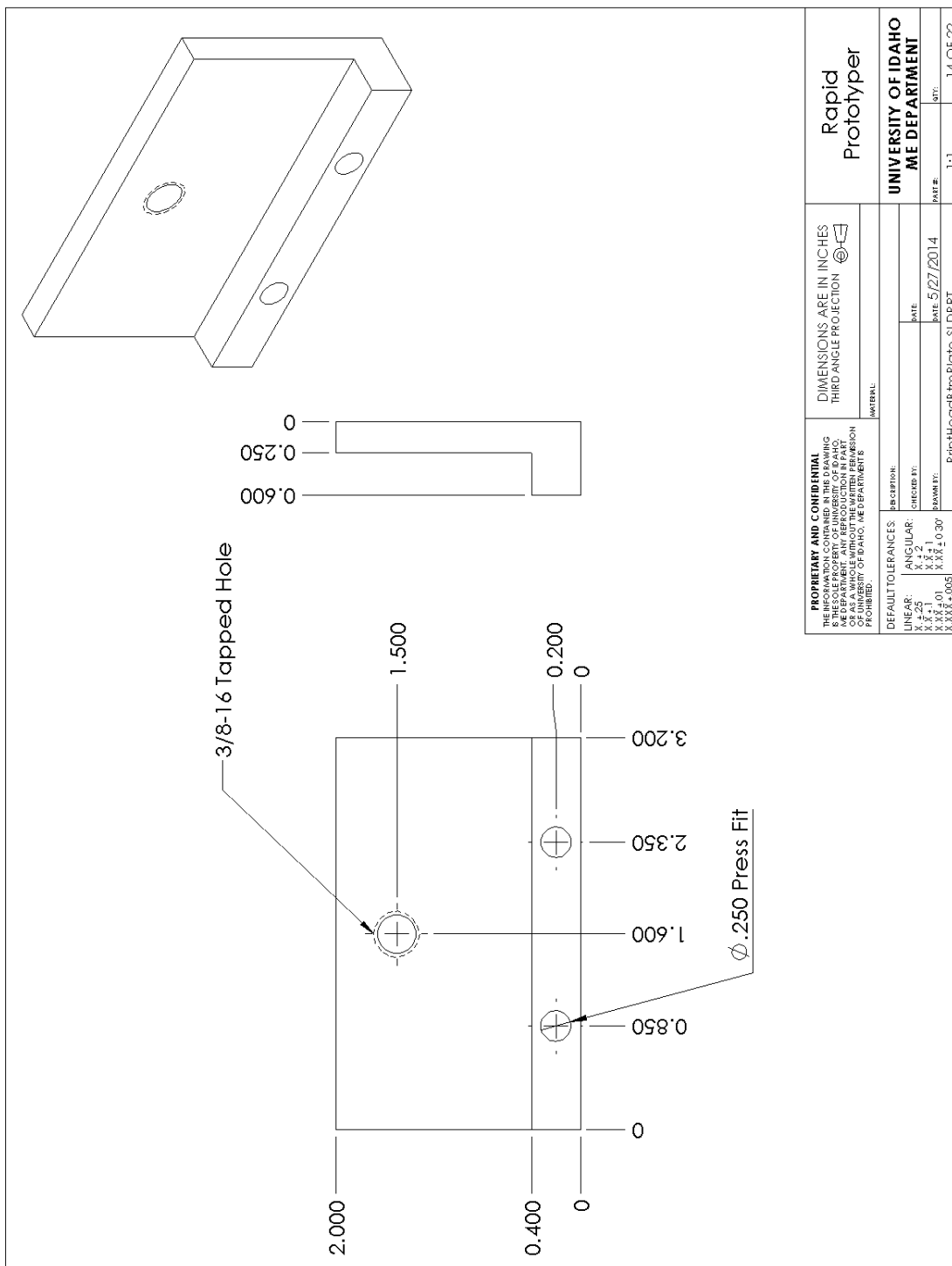




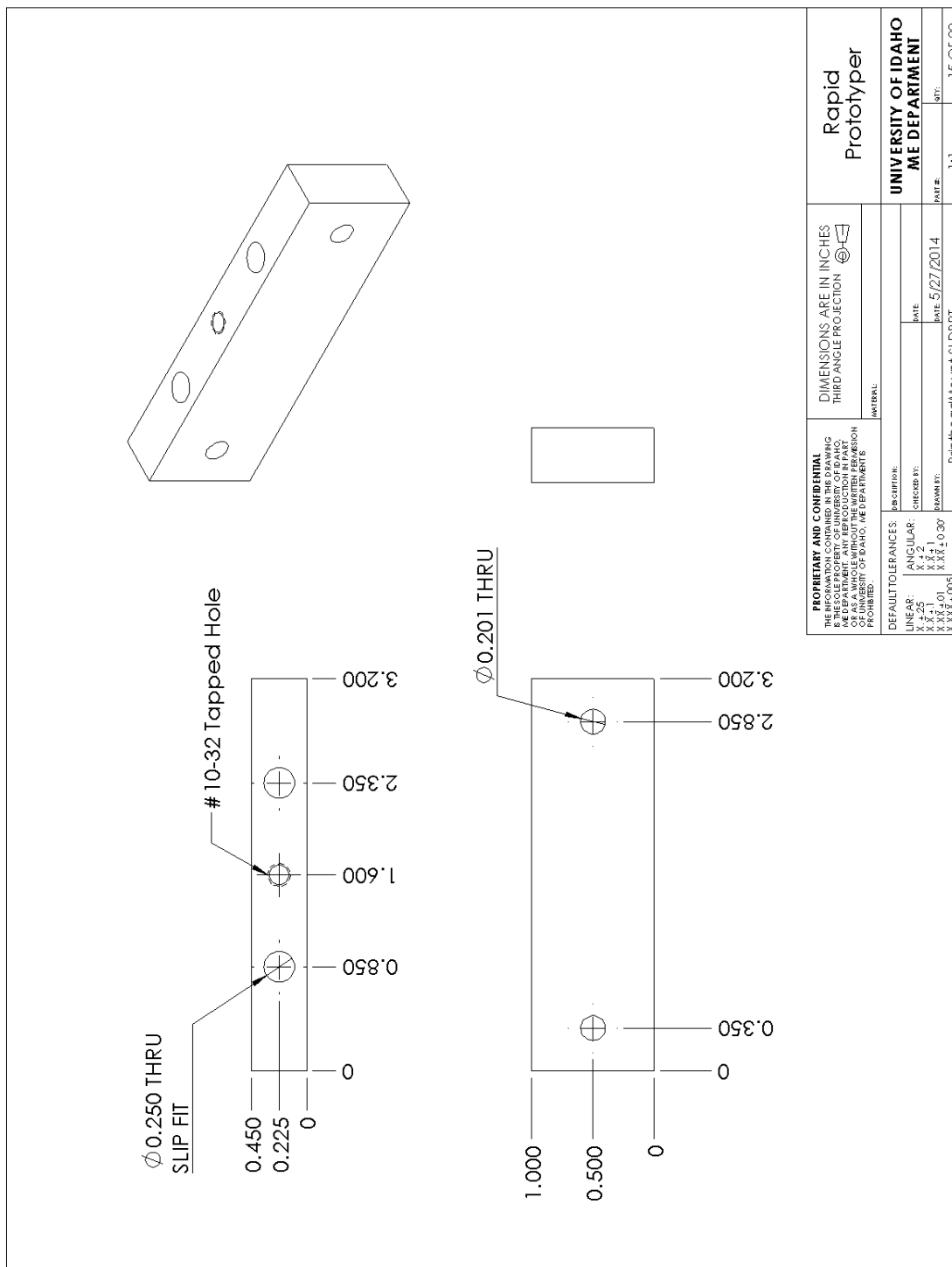


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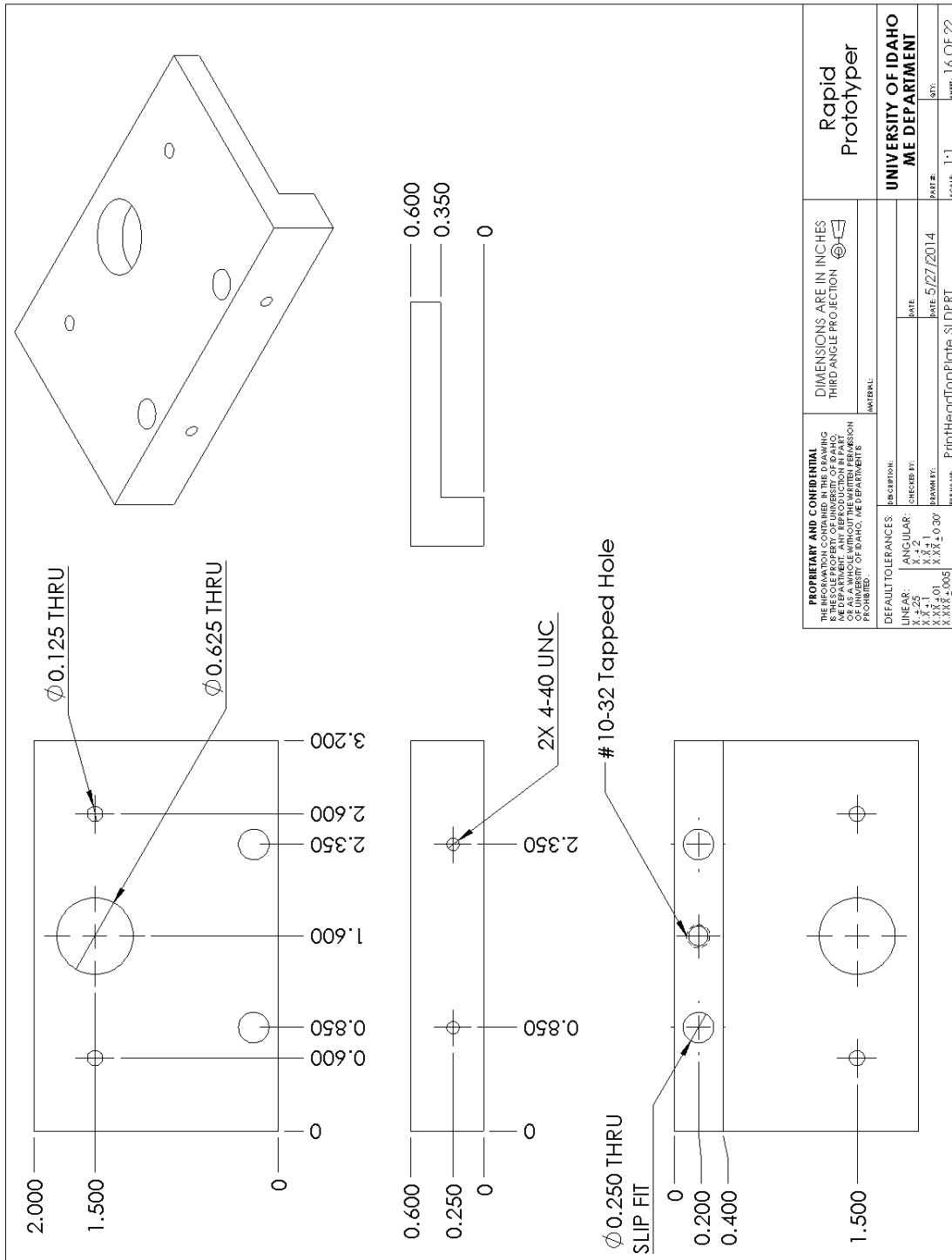




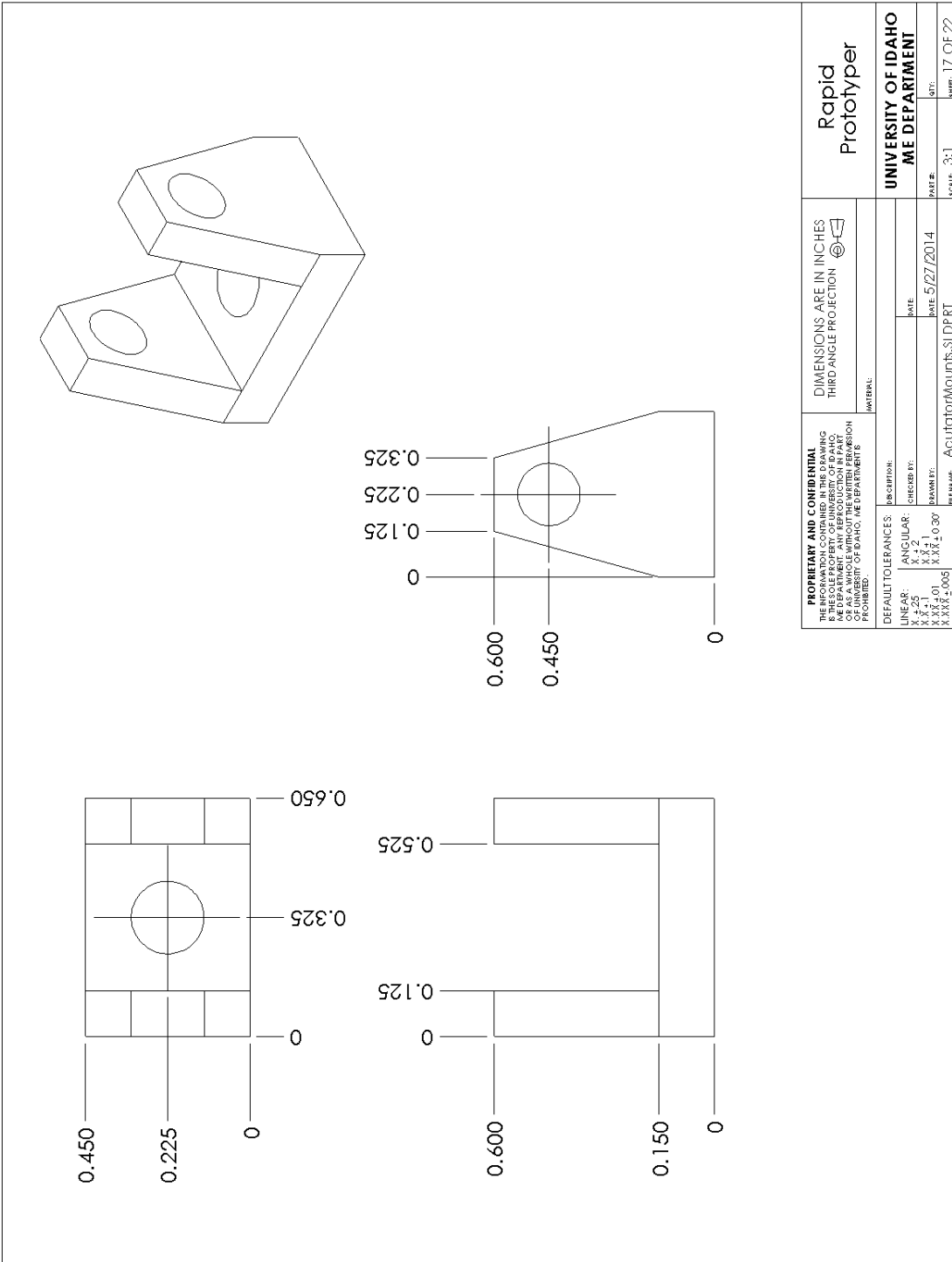
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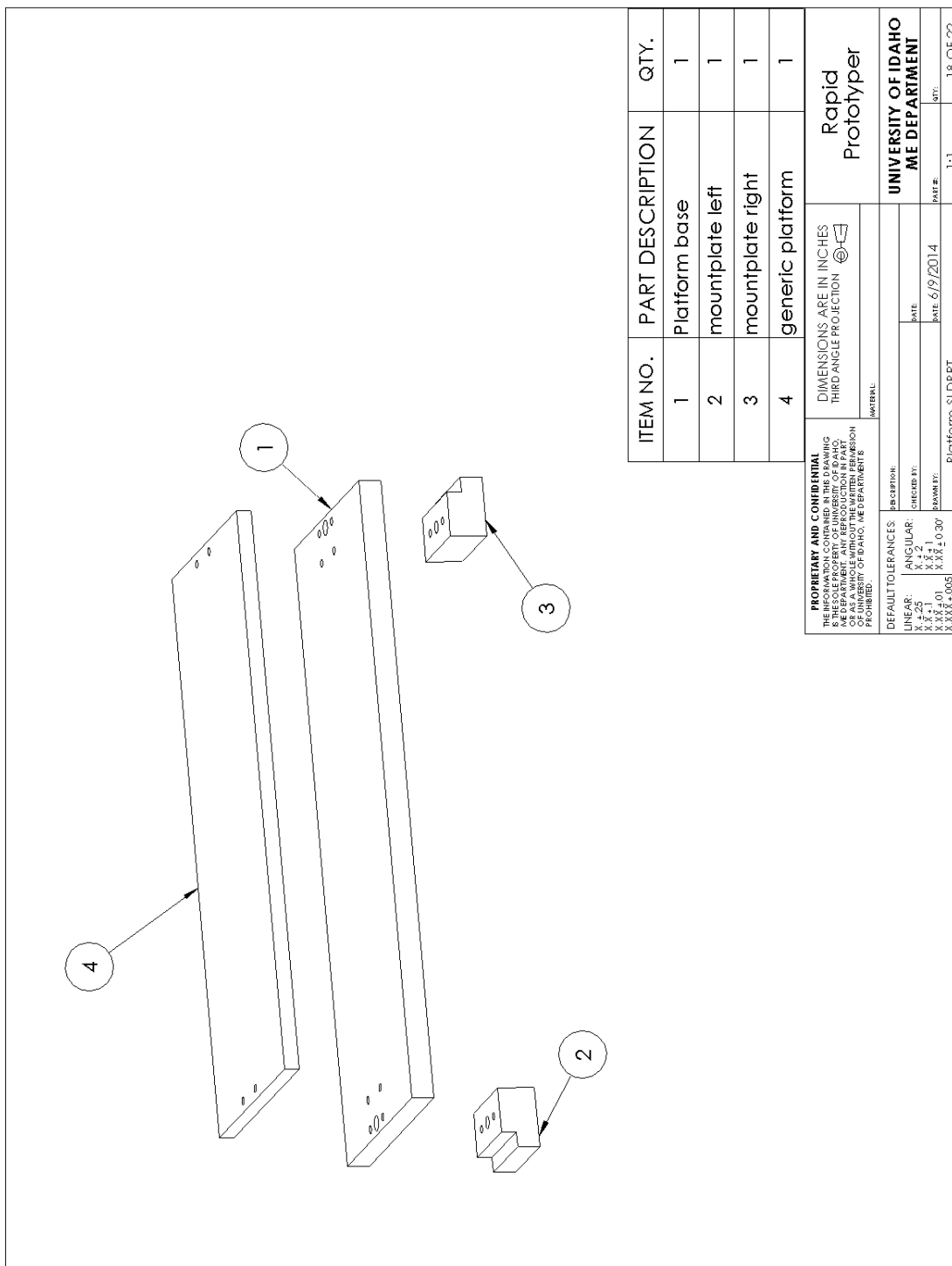


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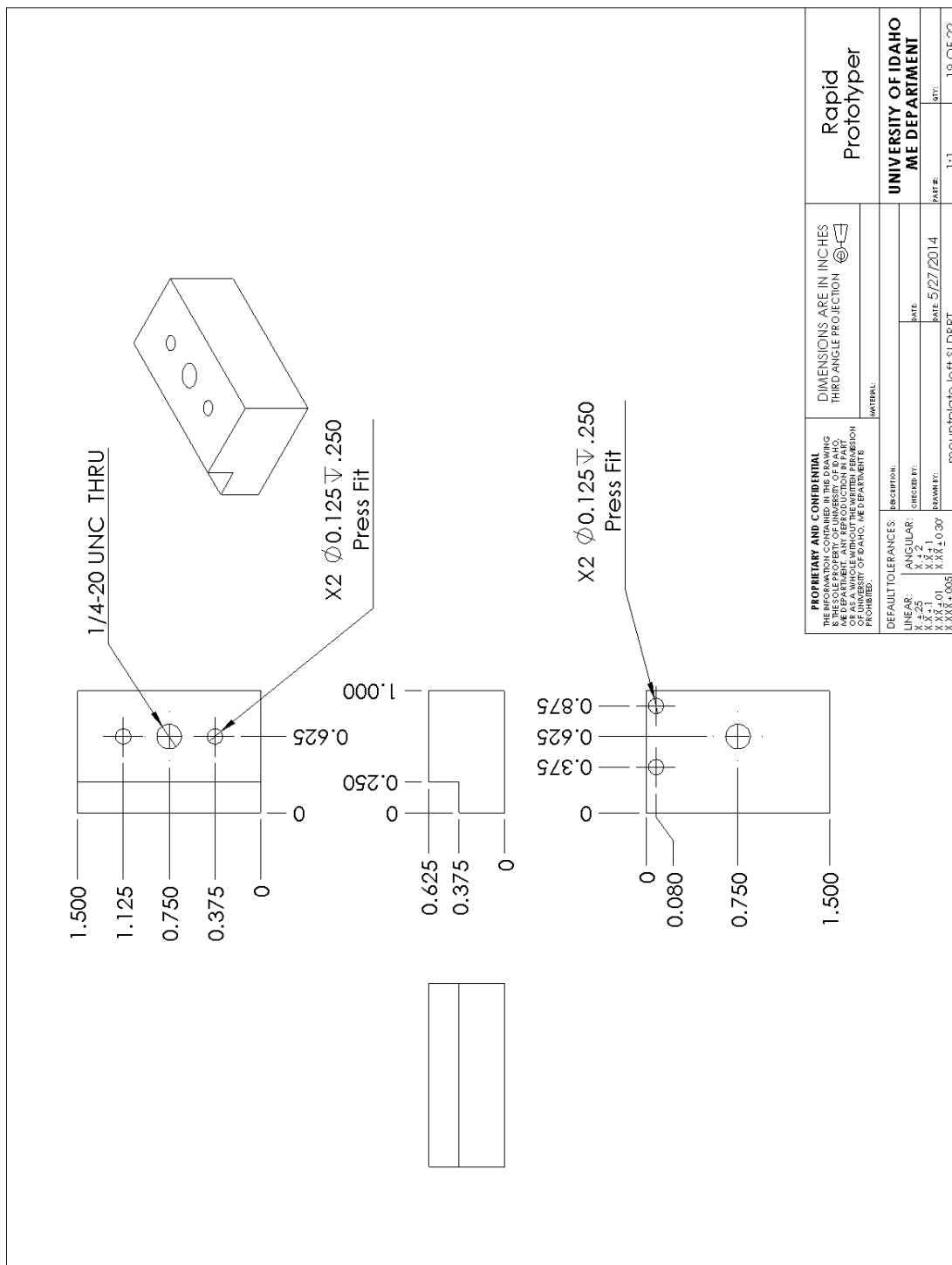
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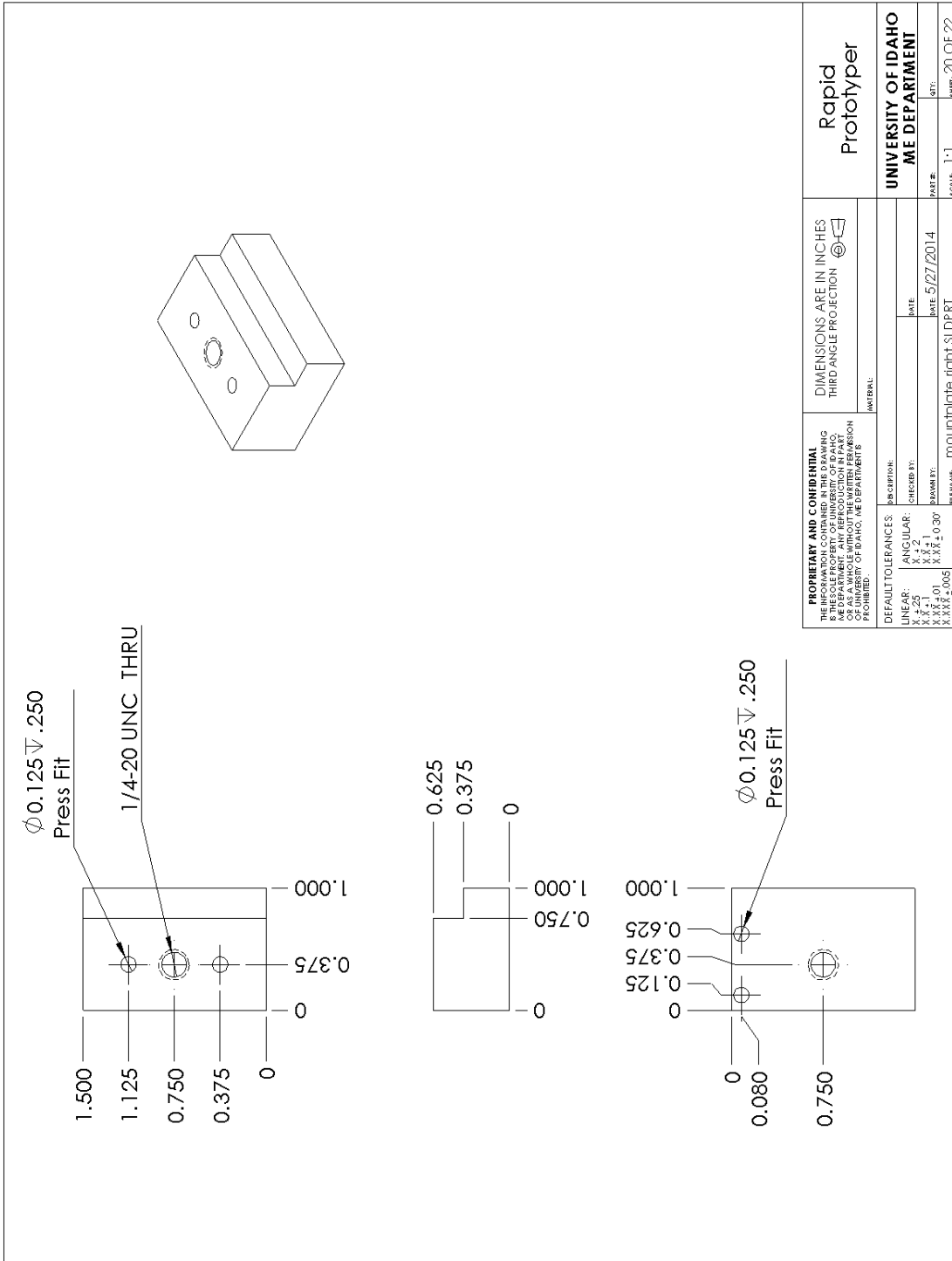
DIMENSIONS ARE IN INCHES
 THIRD ANGLE PROJECTION

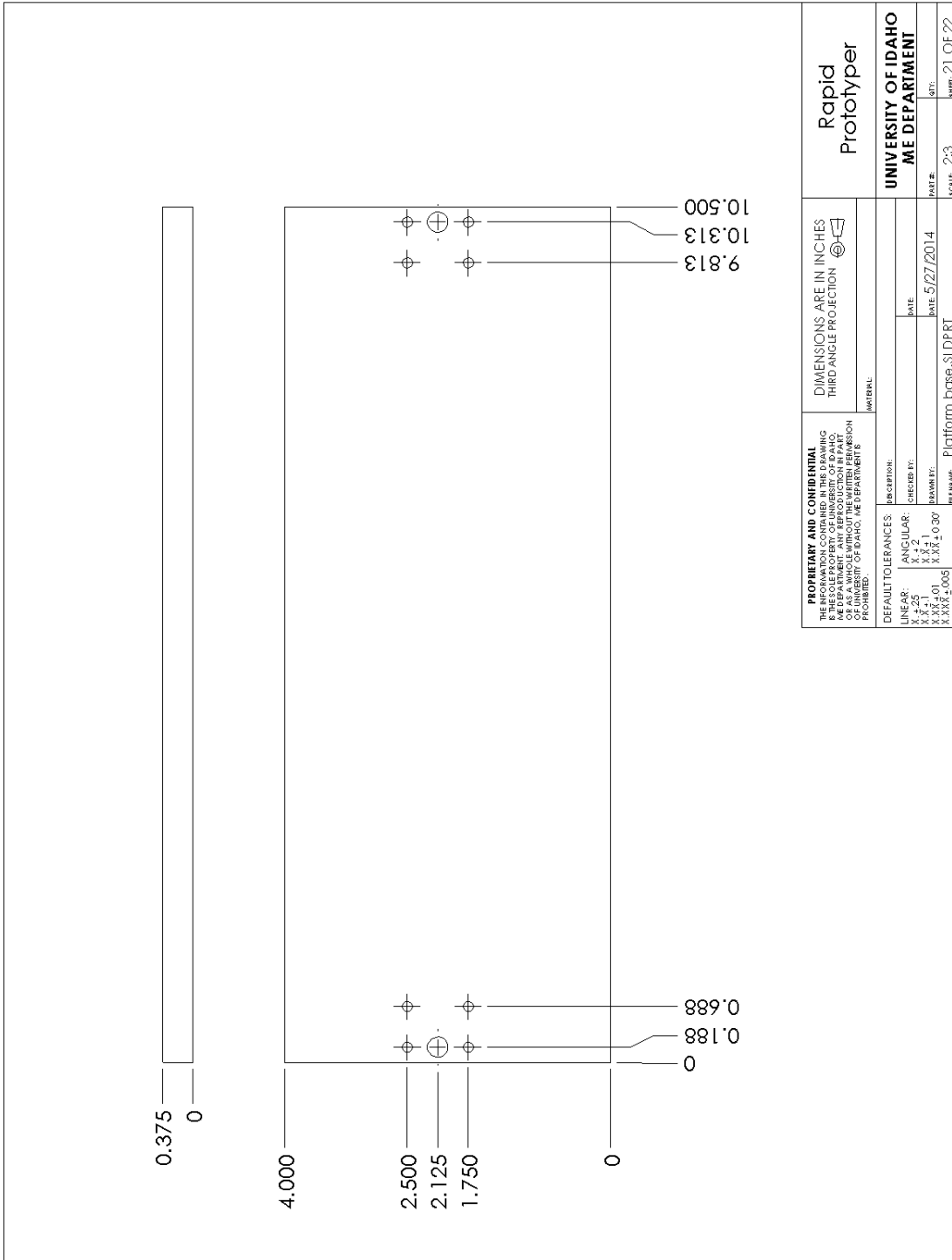
DEFAULT TOLERANCES:
 LINEAR: X ±.25
 ANGLE: X ±.2
 X ±.1
 X ±.030
 X ±.005

UNIVERSITY OF IDAHO
 ME DEPARTMENT

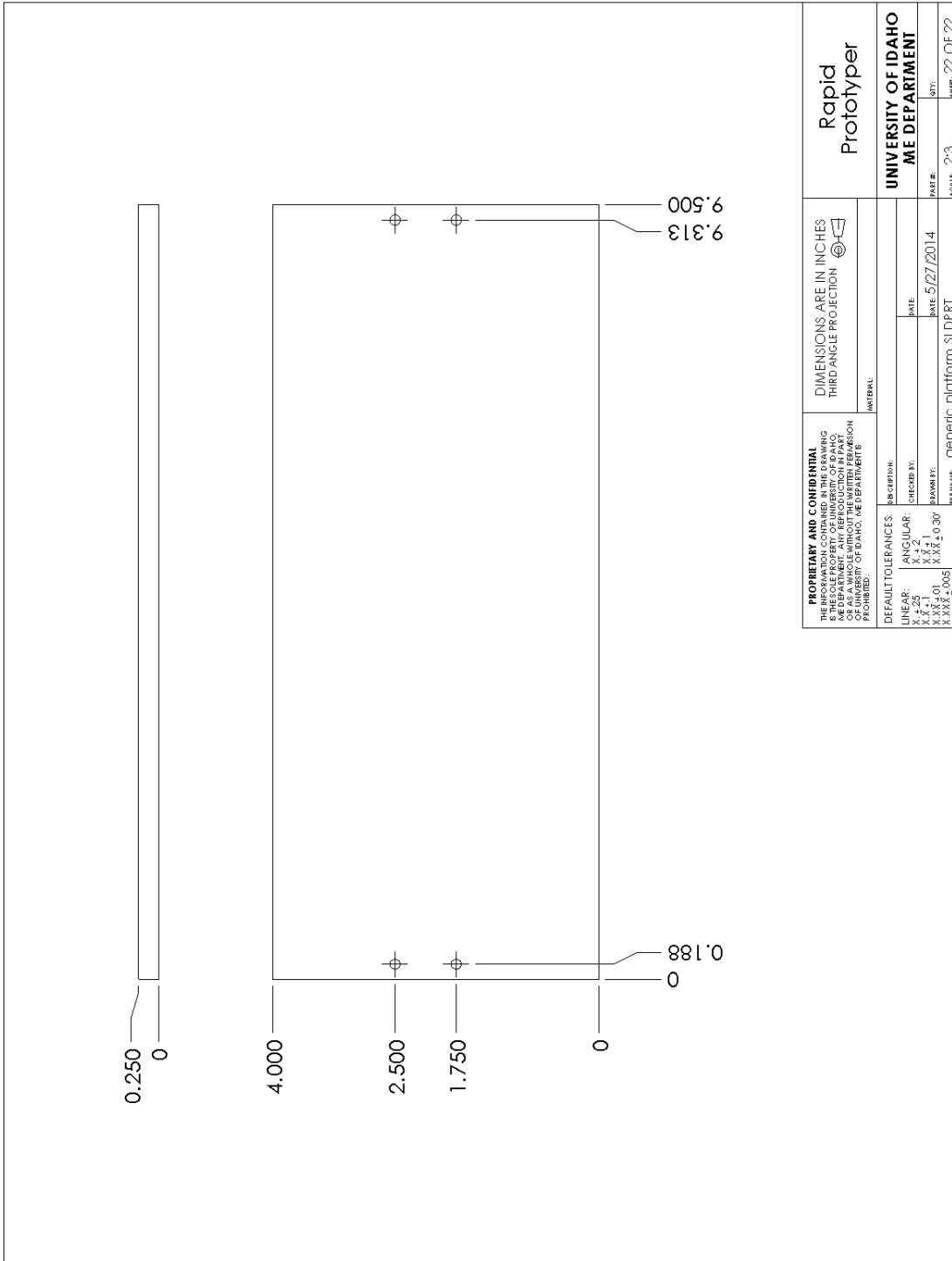
Rapid
 Prototyper







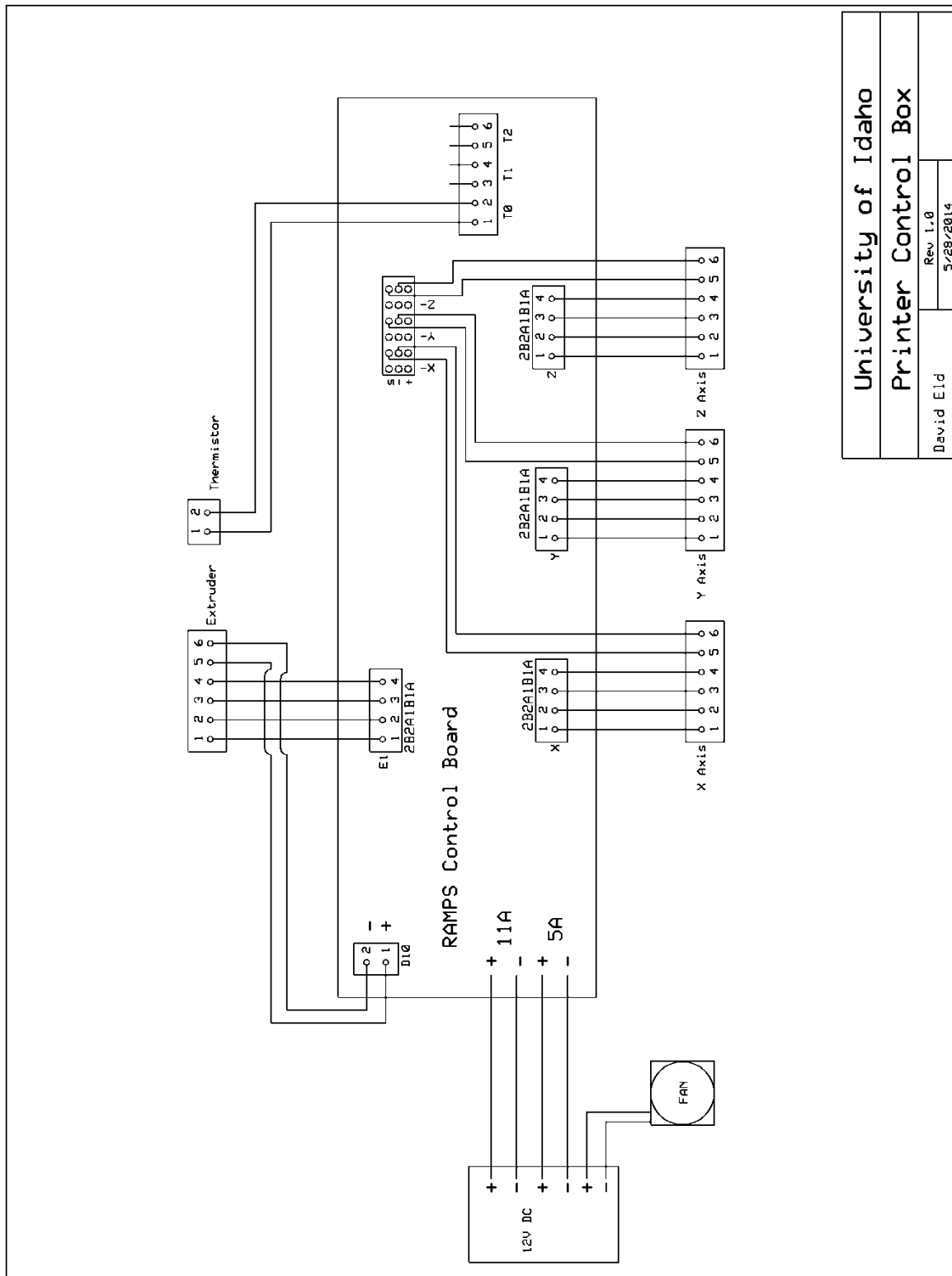
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	DESCRIPTION: Platform base.SLDprt		UNIVERSITY OF IDAHO ME DEPARTMENT	
DEFAULT TOLERANCES: LINEAR: X ± .25 X ± .1 X ± .1 X ± .005	ANGLE: X ± 2 X ± 1 X ± 0.30	CHECKED BY:	DATE: 5/27/2014	PART #:
MATERIAL:		DRAWN BY:	DATE:	REV:
REVISION:		DATE:		SHEET: 21 OF 22



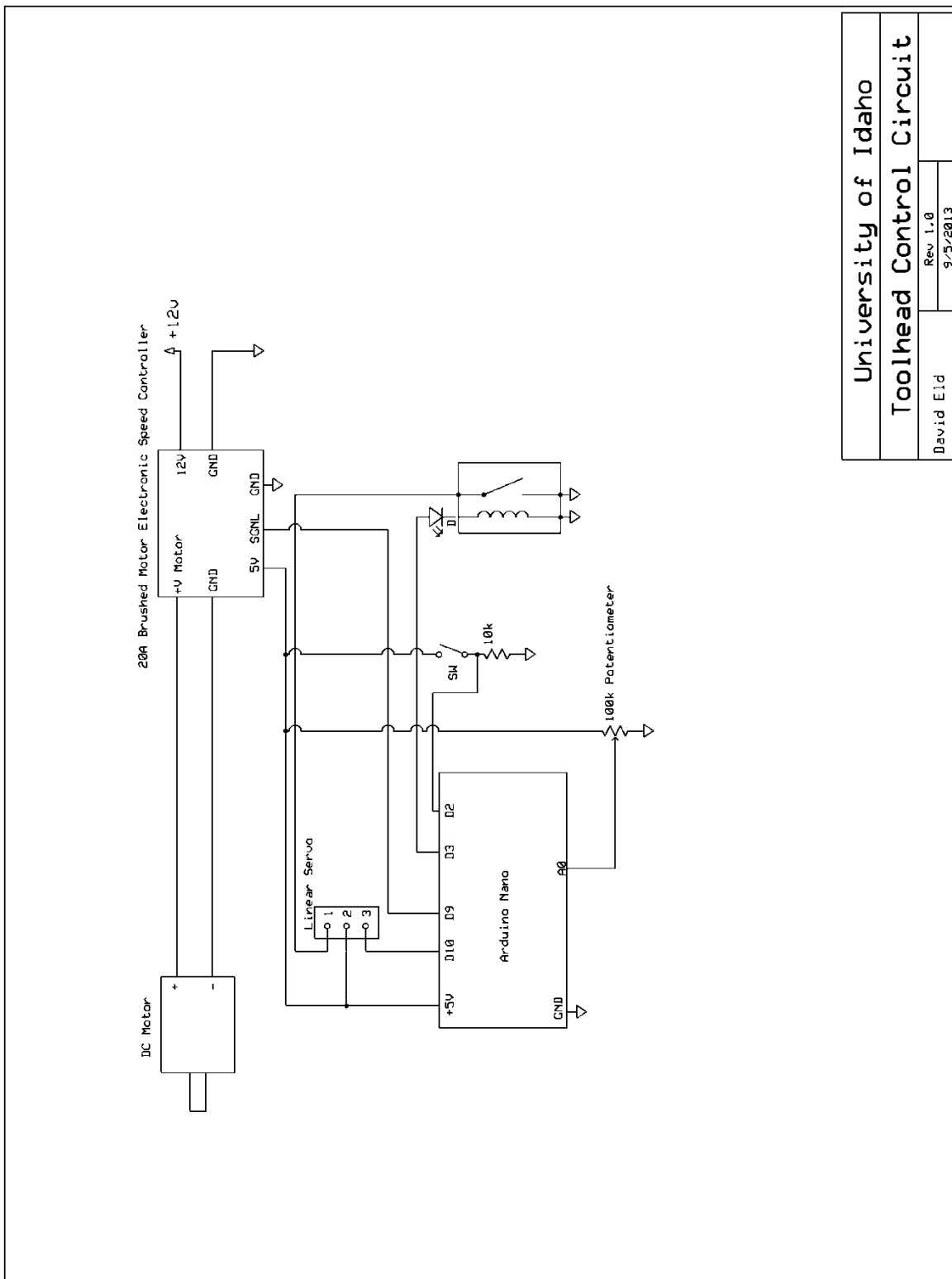
PROPRIETARY AND CONFIDENTIAL THIS DOCUMENT IS THE SOLE PROPERTY OF UNIVERSITY OF IDAHO. IT IS TO BE USED ONLY FOR THE REPRODUCTION OF THIS PART OF UNIVERSITY OF IDAHO. REPRODUCTION OF THIS PART OF UNIVERSITY OF IDAHO, ME DEPARTMENT IS PROHIBITED.		DIMENSIONS ARE IN INCHES THIRD ANGLE PROJECTION		Rapid Prototyper	
DESCRIPTION: Generic platform.SLDprt		MATERIAL:		UNIVERSITY OF IDAHO ME DEPARTMENT	
CHECKED BY:		DATE:		PART #:	
DRAWN BY:		DATE: 5/27/2014		REV:	
TOLERANCES:		ANGULAR:		SCALE: 2:3	
LINEAR:		X ± .25		SHEET: 22 OF 22	
X ± .1		X ± .1			
X ± .1		X ± .1			
X ± .005		X ± .005			

Appendix II

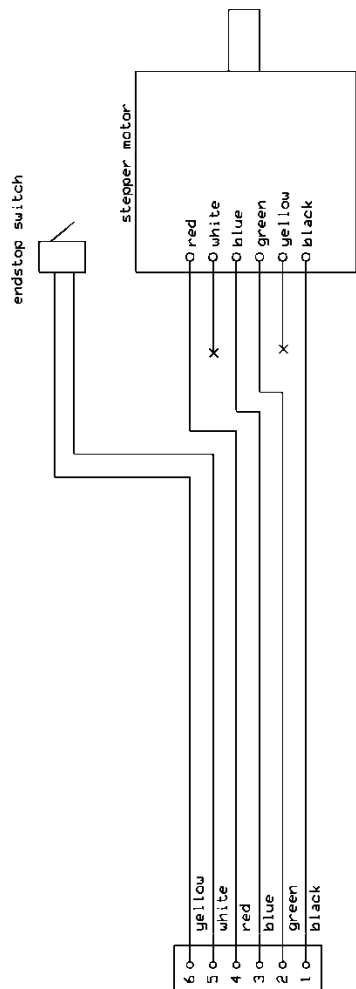
Electrical Schematics



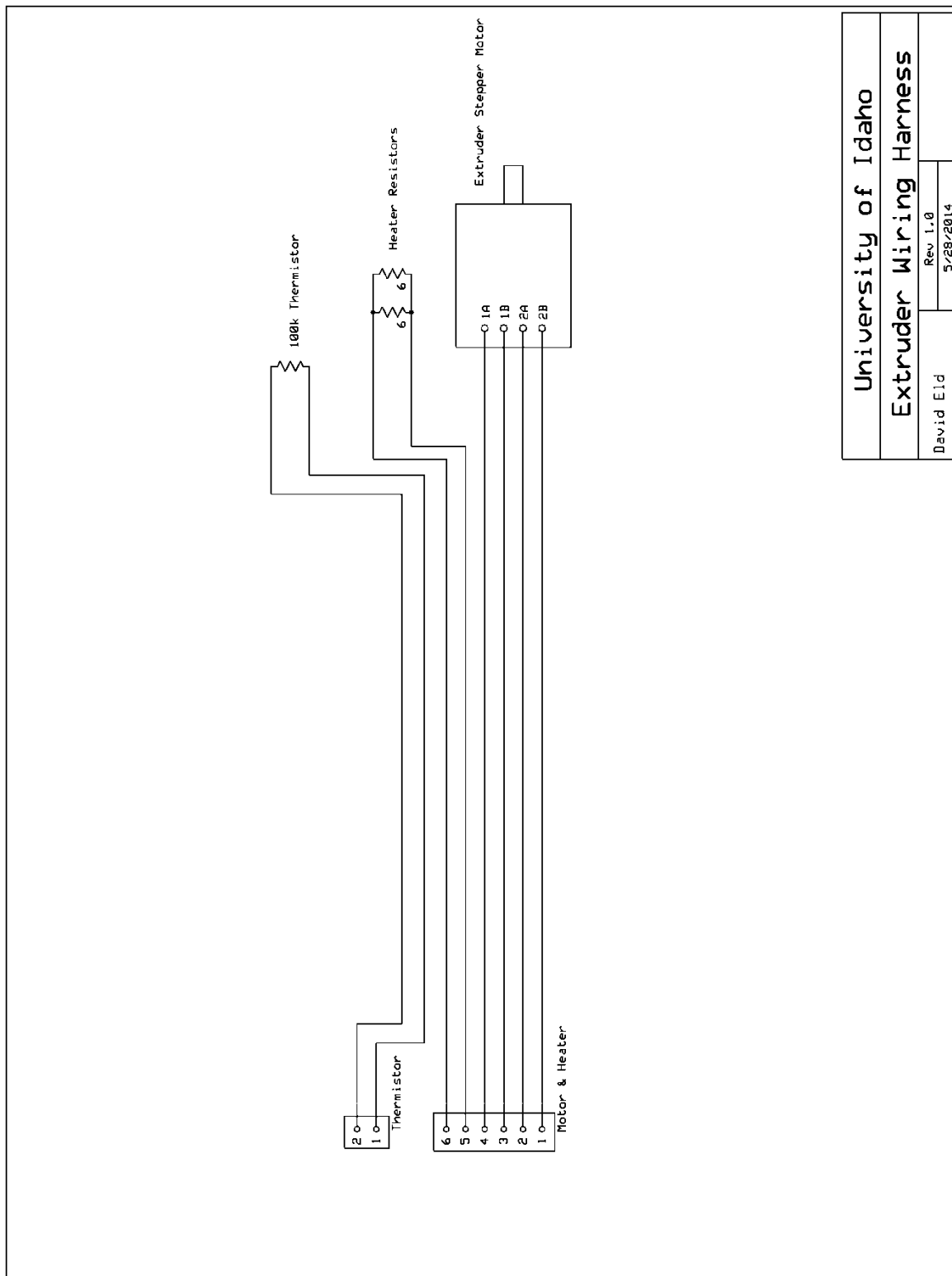
University of Idaho
 Printer Control Box
 David Eid
 Rev 1.0
 5/28/2014



University of Idaho	
Toolhead Control Circuit	
David Eid	Rev 1.0
	9/5/2013



University of Idaho	
Axis Motor Harness	
Designer's name	Rev 1.0
	5/28/2014



University of Idaho	
Extruder Wiring Harness	
David Eid	Rev 1.0 5/28/2014

Appendix III

Prototyper Config.H Code

```
#ifndef CONFIGURATION_H

#define CONFIGURATION_H

// This configuration file contains the basic settings.

// Advanced settings can be found in Configuration_adv.h

// BASIC SETTINGS: select your board type, temperature sensor type, axis scaling, and
endstop configuration

//User specified version info of this build to display in [Pronterface, etc] terminal window
during startup.

//Implementation of an idea by Prof Braino to inform user that any changes made

//to this build by the user have been successfully uploaded into firmware.

#define STRING_VERSION_CONFIG_H __DATE__ " " __TIME__ // build date and time

#define STRING_CONFIG_H_AUTHOR "(none, default config)" //Who made the changes.

// SERIAL_PORT selects which serial port should be used for communication with the host.

// This allows the connection of wireless adapters (for instance) to non-default port pins.

// Serial port 0 is still used by the Arduino bootloader regardless of this setting.
```

```
#define SERIAL_PORT 0

// This determines the communication speed of the printer

#define BAUDRATE 250000

//#define BAUDRATE 115200

//// The following define selects which electronics board you have. Please choose the one
that matches your setup

// 10 = Gen7 custom (Alfons3 Version)
"https://github.com/Alfons3/Generation_7_Electronics"

// 11 = Gen7 v1.1, v1.2 = 11

// 12 = Gen7 v1.3

// 13 = Gen7 v1.4

// 3 = MEGA/RAMPS up to 1.2 = 3

// 33 = RAMPS 1.3 / 1.4 (Power outputs: Extruder, Bed, Fan)

// 34 = RAMPS 1.3 / 1.4 (Power outputs: Extruder0, Extruder1, Bed)

// 4 = Duemilanove w/ ATmega328P pin assignment

// 5 = Gen6
```

// 51 = Gen6 deluxe

// 6 = Sanguinololu < 1.2

// 62 = Sanguinololu 1.2 and above

// 63 = Melzi

// 64 = STB V1.1

// 7 = Ultimaker

// 71 = Ultimaker (Older electronics. Pre 1.5.4. This is rare)

// 8 = Teensylu

// 80 = Rumba

// 81 = Printrboard (AT90USB1286)

// 82 = Brainwave (AT90USB646)

// 9 = Gen3+

// 70 = Megatronics

// 90 = Alpha OMCA board

// 91 = Final OMCA board

// 301 = Rambo

```
#ifndef MOTHERBOARD
```

```
#define MOTHERBOARD 34
```

```
#endif
```

```
//// The following define selects which power supply you have. Please choose the one that  
matches your setup
```

```
// 1 = ATX
```

```
// 2 = X-Box 360 203Watts (the blue wire connected to PS_ON and the red wire to VCC)
```

```
#define POWER_SUPPLY 1
```

```
//=====
```

```
=====
```

```
//=====Thermal Settings
```

```
=====
```

```
//=====
```

```
=====
```

```
//
```

//--NORMAL IS 4.7kohm PULLUP!-- 1kohm pullup can be used on hotend sensor, using correct resistor and table

//

//// Temperature sensor settings:

// -2 is thermocouple with MAX6675 (only for sensor 0)

// -1 is thermocouple with AD595

// 0 is not used

// 1 is 100k thermistor - best choice for EPCOS 100k (4.7k pullup)

// 2 is 200k thermistor - ATC Semitec 204GT-2 (4.7k pullup)

// 3 is mendel-parts thermistor (4.7k pullup)

// 4 is 10k thermistor !! do not use it for a hotend. It gives bad resolution at high temp. !!

// 5 is 100K thermistor - ATC Semitec 104GT-2 (Used in ParCan) (4.7k pullup)

// 6 is 100k EPCOS - Not as accurate as table 1 (created using a fluke thermocouple) (4.7k pullup)

// 7 is 100k Honeywell thermistor 135-104LAG-J01 (4.7k pullup)

// 8 is 100k 0603 SMD Vishay NTCS0603E3104FXT (4.7k pullup)

// 9 is 100k GE Sensing AL03006-58.2K-97-G1 (4.7k pullup)

// 10 is 100k RS thermistor 198-961 (4.7k pullup)


```
//  
  
// 1k ohm pullup tables - This is not normal, you would have to have changed out your  
4.7k for 1k  
  
//          (but gives greater accuracy and more stable PID)  
  
// 51 is 100k thermistor - EPCOS (1k pullup)  
  
// 52 is 200k thermistor - ATC Semitec 204GT-2 (1k pullup)  
  
// 55 is 100k thermistor - ATC Semitec 104GT-2 (Used in ParCan) (1k pullup)  
  
  
#define TEMP_SENSOR_0 7  
  
#define TEMP_SENSOR_1 0  
  
#define TEMP_SENSOR_2 0  
  
#define TEMP_SENSOR_BED 0  
  
  
// Actual temperature must be close to target for this long before M109 returns success  
  
#define TEMP_RESIDENCY_TIME 10    // (seconds)  
  
#define TEMP_HYSTERESIS 3    // (degC) range of +/- temperatures considered "close"  
to the target one
```

```
#define TEMP_WINDOW 1 // (degC) Window around target to start the recidency  
timer x degC early.
```

```
// The minimal temperature defines the temperature below which the heater will not be  
enabled It is used
```

```
// to check that the wiring to the thermistor is not broken.
```

```
// Otherwise this would lead to the heater being powered on all the time.
```

```
#define HEATER_0_MINTEMP 5
```

```
#define HEATER_1_MINTEMP 5
```

```
#define HEATER_2_MINTEMP 5
```

```
#define BED_MINTEMP 5
```

```
// When temperature exceeds max temp, your heater will be switched off.
```

```
// This feature exists to protect your hotend from overheating accidentally, but *NOT* from  
thermistor short/failure!
```

```
// You should use MINTEMP for thermistor short/failure protection.
```

```
#define HEATER_0_MAXTEMP 275
```

```
#define HEATER_1_MAXTEMP 275
```

```
#define HEATER_2_MAXTEMP 275

#define BED_MAXTEMP 150

// If your bed has low resistance e.g. .6 ohm and throws the fuse you can duty cycle it to
reduce the

// average current. The value should be an integer and the heat bed will be turned on for 1
interval of

// HEATER_BED_DUTY_CYCLE_DIVIDER intervals.

//#define HEATER_BED_DUTY_CYCLE_DIVIDER 4

// PID settings:

// Comment the following line to disable PID and enable bang-bang.

#define PIDTEMP

#define BANG_MAX 256 // limits current to nozzle while in bang-bang mode; 256=full
current

#define PID_MAX 256 // limits current to nozzle while PID is active (see
PID_FUNCTIONAL_RANGE below); 256=full current

#ifndef PIDTEMP
```

```
//#define PID_DEBUG // Sends debug data to the serial port.

//#define PID_OPENLOOP 1 // Puts PID in open loop. M104/M140 sets the output power
from 0 to PID_MAX

#define PID_FUNCTIONAL_RANGE 10 // If the temperature difference between the
target temperature and the actual temperature

// is more then PID_FUNCTIONAL_RANGE then the PID will be shut
off and the heater will be set to min/max.

#define PID_INTEGRAL_DRIVE_MAX 255 //limit for the integral term

#define K1 0.95 //smoothing factor withing the PID

#define PID_dT ((16.0 * 8.0)/(F_CPU / 64.0 / 256.0)) //sampling period of the temperature
routine

// If you are using a preconfigured hotend then you can use one of the value sets by
uncommenting it

// Ultimaker

#define DEFAULT_Kp 15.33

#define DEFAULT_Ki 0.99

#define DEFAULT_Kd 59.52
```

```
// Makergear

// #define DEFAULT_Kp 7.0

// #define DEFAULT_Ki 0.1

// #define DEFAULT_Kd 12

// Mendel Parts V9 on 12V

// #define DEFAULT_Kp 63.0

// #define DEFAULT_Ki 2.25

// #define DEFAULT_Kd 440

#endif // PIDTEMP

// Bed Temperature Control

// Select PID or bang-bang with PIDTEMPBED. If bang-bang, BED_LIMIT_SWITCHING
will enable hysteresis

//

// uncomment this to enable PID on the bed. It uses the same frequency PWM as the
extruder.
```

```
// If your PID_dT above is the default, and correct for your hardware/configuration, that
means 7.689Hz,

// which is fine for driving a square wave into a resistive load and does not significantly
impact you FET heating.

// This also works fine on a Fotek SSR-10DA Solid State Relay into a 250W heater.

// If your configuration is significantly different than this and you don't understand the issues
involved, you probably

// shouldn't use bed PID until someone else verifies your hardware works.

// If this is enabled, find your own PID constants below.

//#define PIDTEMPBED

//

//#define BED_LIMIT_SWITCHING

// This sets the max power delivered to the bed, and replaces the
HEATER_BED_DUTY_CYCLE_DIVIDER option.

// all forms of bed control obey this (PID, bang-bang, bang-bang with hysteresis)

// setting this to anything other than 256 enables a form of PWM to the bed just like
HEATER_BED_DUTY_CYCLE_DIVIDER did,
```

```
// so you shouldn't use it unless you are OK with PWM on your bed. (see the comment on  
enabling PIDTEMPBED)
```

```
#define MAX_BED_POWER 256 // limits duty cycle to bed; 256=full current
```

```
#ifdef PIDTEMPBED
```

```
//120v 250W silicone heater into 4mm borosilicate (MendelMax 1.5+)
```

```
//from FOPDT model - kp=.39 Tp=405 Tdead=66, Tc set to 79.2, argressive factor of .15 (vs  
.1, 1, 10)
```

```
#define DEFAULT_bedKp 10.00
```

```
#define DEFAULT_bedKi .023
```

```
#define DEFAULT_bedKd 305.4
```

```
//120v 250W silicone heater into 4mm borosilicate (MendelMax 1.5+)
```

```
//from pidautotune
```

```
// #define DEFAULT_bedKp 97.1
```

```
// #define DEFAULT_bedKi 1.41
```

```
// #define DEFAULT_bedKd 1675.16
```

```
// FIND YOUR OWN: "M303 E-1 C8 S90" to run autotune on the bed at 90 degreesC for 8
cycles.
```

```
#endif // PIDTEMPBED
```

```
//this prevents dangerous Extruder moves, i.e. if the temperature is under the limit
```

```
//can be software-disabled for whatever purposes by
```

```
#define PREVENT_DANGEROUS_EXTRUDE
```

```
//if PREVENT_DANGEROUS_EXTRUDE is on, you can still disable (uncomment) very
long bits of extrusion separately.
```

```
#define PREVENT_LENGTHY_EXTRUDE
```

```
#define EXTRUDE_MINTEMP 170
```

```
#define EXTRUDE_MAXLENGTH (X_MAX_LENGTH+Y_MAX_LENGTH) //prevent
extrusion of very large distances.
```



```
//=====
```

```
=====
```

```
//=====Mechanical
```

```
Settings=====
```

```
//=====
```

```
=====
```

```
// Uncomment the following line to enable CoreXY kinematics
```

```
// #define COREXY
```

```
// corse Endstop Settings
```

```
#define ENDSTOPPULLUPS // Comment this out (using // at the start of the line) to disable  
the endstop pullup resistors
```

```
#ifndef ENDSTOPPULLUPS
```

```
    // fine Enstop settings: Individual Pullups. will be ignord if ENDSTOPPULLUPS is  
defined
```

```
#define ENDSTOPPULLUP_XMAX
```

```
#define ENDSTOPPULLUP_YMAX
```

```
#define ENDSTOPPULLUP_ZMAX

// #define ENDSTOPPULLUP_XMIN

// #define ENDSTOPPULLUP_YMIN

// #define ENDSTOPPULLUP_ZMIN

#endif

#ifdef ENDSTOPPULLUPS

#define ENDSTOPPULLUP_XMAX

#define ENDSTOPPULLUP_YMAX

#define ENDSTOPPULLUP_ZMAX

// #define ENDSTOPPULLUP_XMIN

// #define ENDSTOPPULLUP_YMIN

// #define ENDSTOPPULLUP_ZMIN

#endif

// The pullups are needed if you directly connect a mechanical endswitch between the signal
and ground pins.
```

```
const bool X_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the
endstops.
```

```
const bool Y_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the
endstops.
```

```
const bool Z_ENDSTOPS_INVERTING = false; // set to true to invert the logic of the
endstops.
```

```
//#define DISABLE_MAX_ENDSTOPS
```

```
// For Inverting Stepper Enable Pins (Active Low) use 0, Non Inverting (Active High) use 1
```

```
#define X_ENABLE_ON 0
```

```
#define Y_ENABLE_ON 0
```

```
#define Z_ENABLE_ON 0
```

```
#define E_ENABLE_ON 0 // For all extruders
```

```
// Disables axis when it's not being used.
```

```
#define DISABLE_X true
```

```
#define DISABLE_Y true
```

```
#define DISABLE_Z true
```

```
#define DISABLE_E false // For all extruders

#define INVERT_X_DIR false // for Mendel set to false, for Orca set to true

#define INVERT_Y_DIR true // for Mendel set to true, for Orca set to false

#define INVERT_Z_DIR true // for Mendel set to false, for Orca set to true

#define INVERT_E0_DIR false // for direct drive extruder v9 set to true, for geared
extruder set to false

#define INVERT_E1_DIR false // for direct drive extruder v9 set to true, for geared
extruder set to false

#define INVERT_E2_DIR false // for direct drive extruder v9 set to true, for geared
extruder set to false

// ENDSTOP SETTINGS:

// Sets direction of endstops when homing; 1=MAX, -1=MIN

#define X_HOME_DIR 1

#define Y_HOME_DIR 1

#define Z_HOME_DIR 1
```

```
#define min_software_endstops false //If true, axis won't move to coordinates less than
HOME_POS.

#define max_software_endstops false//If true, axis won't move to coordinates greater than
the defined lengths below.

// Travel limits after homing

#define X_MAX_POS 150

#define X_MIN_POS 0

#define Y_MAX_POS 100

#define Y_MIN_POS 0

#define Z_MAX_POS 131.2

#define Z_MIN_POS -15

#define X_MAX_LENGTH (X_MAX_POS - X_MIN_POS)

#define Y_MAX_LENGTH (Y_MAX_POS - Y_MIN_POS)

#define Z_MAX_LENGTH (Z_MAX_POS - Z_MIN_POS)

// The position of the homing switches
```

```
#define MANUAL_HOME_POSITIONS // If defined, MANUAL_*_HOME_POS below  
will be used
```

```
//#define BED_CENTER_AT_0_0 // If defined, the center of the bed is at (X=0, Y=0)
```

```
//Manual homing switch locations:
```

```
#define MANUAL_X_HOME_POS 150
```

```
#define MANUAL_Y_HOME_POS 100
```

```
#define MANUAL_Z_HOME_POS 131.2
```

```
//// MOVEMENT SETTINGS
```

```
#define NUM_AXIS 4 // The axis order in all axis related arrays is X, Y, Z, E
```

```
#define HOMING_FEEDRATE {150, 150, 150, 0} // set the homing speeds (mm/min)
```

```
// default settings
```

```
#define DEFAULT_AXIS_STEPS_PER_UNIT
```

```
{2*157.4803,2*157.4803,2*157.4803,619} // default steps per unit for ultimaker
```

```
#define DEFAULT_MAX_FEEDRATE {10, 10, 10, 25} // (mm/sec)
```

```
#define DEFAULT_MAX_ACCELERATION {3,3,3,10000} // X, Y, Z, E maximum  
start speed for accelerated moves. E default values are good for skeinforge 40+, for older  
versions raise them a lot.
```

```
#define DEFAULT_ACCELERATION 2 // X, Y, Z and E max acceleration in  
mm/s^2 for printing moves
```

```
#define DEFAULT_RETRACT_ACCELERATION 500 // X, Y, Z and E max  
acceleration in mm/s^2 for r retracts
```

```
// Offset of the extruders (uncomment if using more than one and relying on firmware to  
position when changing).
```

```
// The offset has to be X=0, Y=0 for the extruder 0 hotend (default extruder).
```

```
// For the other hotends it is their distance from the extruder 0 hotend.
```

```
// #define EXTRUDER_OFFSET_X {0.0, 20.00} // (in mm) for each extruder, offset of the  
hotend on the X axis
```

```
// #define EXTRUDER_OFFSET_Y {0.0, 5.00} // (in mm) for each extruder, offset of the  
hotend on the Y axis
```

```
// The speed change that does not require acceleration (i.e. the software might assume it can
be done instantaneously)
```

```
#define DEFAULT_XYJERK      2.0 // (mm/sec)
```

```
#define DEFAULT_ZJERK      0.4 // (mm/sec)
```

```
#define DEFAULT_EJERK      5.0 // (mm/sec)
```

```
//=====
```

```
=====
```

```
//=====Additional
```

```
Features=====
```

```
//=====
```

```
=====
```

```
// EEPROM
```

```
// the microcontroller can store settings in the EEPROM, e.g. max velocity...
```

```
// M500 - stores paramters in EEPROM
```

```
// M501 - reads parameters from EEPROM (if you need reset them after you changed them
temporarily).
```



```
// M502 - reverts to the default "factory settings". You still need to store them in EEPROM afterwards if you want to.
```

```
//define this to enable eeprom support
```

```
//#define EEPROM_SETTINGS
```

```
//to disable EEPROM Serial responses and decrease program space by ~1700 byte: comment this out:
```

```
// please keep turned on if you can.
```

```
//#define EEPROM_CHITCHAT
```

```
//LCD and SD support
```

```
//#define ULTRA_LCD //general lcd support, also 16x2
```

```
//#define DOGLCD // Support for SPI LCD 128x64 (Controller ST7565R graphic Display Family)
```

```
//#define SDSUPPORT // Enable SD Card Support in Hardware Console
```

```
//#define ULTIMAKERCONTROLLER //as available from the ultimaker online store.
```

```
//#define ULTIPANEL //the ultipanel as on thingiverse
```

```
// The RepRapDiscount Smart Controller (white PCB)

// http://reprap.org/wiki/RepRapDiscount\_Smart\_Controller

//#define REPRAP_DISCOUNT_SMART_CONTROLLER

// The GADGETS3D G3D LCD/SD Controller (blue PCB)

// http://reprap.org/wiki/RAMPS\_1.3/1.4\_GADGETS3D\_Shield\_with\_Panel

//#define G3D_PANEL

//automatic expansion

#if defined(ULTIMAKERCONTROLLER) ||
defined(REPRAP_DISCOUNT_SMART_CONTROLLER) || defined(G3D_PANEL)

#define ULTIPANEL

#define NEWPANEL

#endif

// Preheat Constants

#define PLA_PREHEAT_HOTEND_TEMP 180

#define PLA_PREHEAT_HPB_TEMP 70
```

```
#define PLA_PREHEAT_FAN_SPEED 255 // Insert Value between 0 and 255

#define ABS_PREHEAT_HOTEND_TEMP 240

#define ABS_PREHEAT_HP_B_TEMP 100

#define ABS_PREHEAT_FAN_SPEED 255 // Insert Value between 0 and
255

#ifdef ULTIPANEL

// #define NEWPANEL //enable this if you have a click-encoder panel

#define SDSUPPORT

#define ULTRA_LCD

#ifdef DOGLCD // Change number of lines to match the DOG graphic display

#define LCD_WIDTH 20

#define LCD_HEIGHT 5

#else

#define LCD_WIDTH 20

#define LCD_HEIGHT 4
```

```
#endif

#else //no panel but just lcd

#ifdef ULTRA_LCD

#ifdef DOGLCD // Change number of lines to match the 128x64 graphics
display

#define LCD_WIDTH 20

#define LCD_HEIGHT 5

#else

#define LCD_WIDTH 16

#define LCD_HEIGHT 2

#endif

#endif

#endif

#endif

// Increase the FAN pwm frequency. Removes the PWM noise but increases heating in the
FET/Arduino

//#define FAST_PWM_FAN
```

```
// M240 Triggers a camera by emulating a Canon RC-1 Remote

// Data from: http://www.doc-diy.net/photo/rc-1\_hacked/

// #define PHOTOGRAPH_PIN 23

// SF send wrong arc g-codes when using Arc Point as fillet procedure

// #define SF_ARC_FIX

#include "Configuration_adv.h"

#include "thermistortables.h"

#endif // __CONFIGURATION_H
```