3D Printing Using a PA12/NdFeB Filament

A Major Qualifying Project
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Degree of Bachelor of Science

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This report represents the work of one of more WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirements. WPI routinely publishes these reports on its web site without editorial or peer review

CONTENTS

Table of Figures

Table of Tables

Table of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
BAAM	Big Area Additive Manufacturing
CAD	Computer Aided Design
FDM	Fused Deposition Modeling
Fe	Iron
NdFeB	Neodymium Boron Iron
ORNL	Oak Ridge National Laboratory
PA12	Nylon-12
PID	Proportional Integral Derivative
PLA	Polylactic Acid
SSE	Single Screw Extruder
wt%	Weight Percentage

Acknowledgements

We would like to thank Professor Stabile for his constant support and guidance throughout the course of this project. We would also like to thank Professor Kmiotek for his assistance in using the Chemistry Lab ovens and Edward Burnham for his guidance in coding the Arduino board for the 3D printer.

Authorship

Below is a breakdown of the report by chapter, section and appendices. The section numbers in each chapter represent the sections of the report that each author contributed to.

Tyler Rauch:
Background: 2.1, 2.2, 2.3
Chapter 4
Chapter 6: Conclusions

Kyle Opiekun:
Chapter 5
Chapter 6: Recommendations

Miles Nallen:
Introduction
Background: 2.4, 2.5, 2.6, 2.7
Chapter 3
Professional Writing MQP

4/3 MQP Format

This document contains the necessary requirements to fulfill the 4/3 MQP requirements for a double major in mechanical engineering and professional writing. As a result, this document contains two separate reports and projects. The first report is the mechanical engineering MQP report and the second report is the professional writing mqp report. They are related, since the project was a 4/3 MQP however, the mechanical engineering MQP was worked on by Tyler Rauch, Miles Nallen, and Kyle Opiekun, while the professional writing mqp was only worked on by Miles Nallen.

Abstract

The purpose of this project was to design, build, and modify a conventional 3D printer with the goal of printing magnetic parts. The ability to 3D print NdFeB magnets allows for greater design freedom as well as lower costs, since the NdFeB is mixed with PA 12 Nylon plastic. The first step in this process was designing and building the 3D printer. Once this was accomplished the filament was developed with a weight ratio percentage of 20% NdFeB to 80% PA 12 Nylon. Following the development of the filament, a solenoid was constructed. This solenoid was then placed on the nozzle of the 3D printer in order to align the magnetic particles during the printing process. Future work will focus on optimizing the nozzle and the applied magnetic fields to enhance the residual magnetic strengths and geometries.

1. Introduction

Additive Manufacturing or 3D printing has been around since the 1980's, however, has rapidly gained popularity in the past ten to fifteen years (Goldberg, 2018). One of the innovations that led to 3D printing technology becoming more widely available was Dr. Adrian Bowyer's RepRap project in 2005. The goal of the project was to launch an open source printer that could 3D print almost all of its own parts. The increased availability of 3D printers led to research into different types of materials for 3D printing including different types of plastics, such as Nylon and Acrylonitrile butadiene styrene (ABS), and even metal and wood filaments.

The benefit of 3D printing with materials such as metal quickly became apparent. One of the biggest advantages of being able to 3D print different types of metal was prototyping. A part could easily be designed, printed, and tested with the exact material properties that could be achieved through traditional forms of manufacturing. 3D printing metals also greatly reduces material waste since subtracting manufacturing generates metal chips while additive manufacturing uses only what is necessary and lays material down layer by layer (Beamler, 2018). Greater design freedom was also possible and lighter parts could be developed with the ability to create hollow sections and contours that were not possible with traditional manufacturing methods.

In recent years, Oakridge National Laboratories (ORNL) has been working on 3D printing permanent magnets using rare-metals and various types of plastic. They have found that 3D printed permanent magnets were able to yield the same magnetic properties as traditional injection molded permanent magnets (Li et. al, 2016). Professor Christian Huber at the

University of Austria was also able to achieve similar results with 3D printed permanent magnets, however, a length post magnetization process was required in order to achieve the desired magnetic properties (Huber et. al, 2017). ORNL has not revealed any post magnetization process they may have used in producing their 3D printed permanent magnets, but they have stated that they are working on maintaining the alignment of the magnetic particles during the printing process (Li et. al, 2016). This would eliminate the need for post printing magnetization.

For this MQP, a 3D printer was designed and built to be modified to print with Neodymium Boron Iron (NdFeB) PA-12 Nylon filament. The goal was to 3D print permanent magnets. A solenoid was attached to the bottom of the printer nozzle and powered to create an electromagnetic field to ensure the magnetic properties of the print and eliminate the need for post printing magnetization that Huber was forced to use.

2. Background

For this particular project, it was necessary to research the methods of traditionally molding permanent magnets as well as the challenges that come along with working with magnetic materials. For the sake of the 3D printing permanent magnets, research was also carried out in regards to the properties of rare earth metals, such as neodymium, as well as various types of plastics used in 3D printing, and previous research that was conducted on 3D printing permanent magnets.

2.1 3D Printing

Additive Manufacturing (AM) technology, or what is more recently known as 3D printing, is a technology that has emerged over the past few decades which eliminated the need for tooling or machining as seen in more traditional methods. AM has emerged as a solution to shorten the product development cycle, achieve the flexibility to manufacture small batch sizes, and perform manufacturing of complex designed components at a low cost (Singh, Chabra, 2017). Early in the development of this technology, emphasis was directed onto the “touch-and-feel” aspect of the parts that were made. This lead to the name of “rapid prototyping,” in which the visual and functional attributes of designs could be captured by the plastic models created in the additive manufacturing technique. Yet, parts yielded from rapid prototyping improved in quality to where they could replace the existing tools, parts, components, etc. that they originally modeled for. This replacement can be attributed to the increased precision of the 3D printers themselves as well as stronger, more durable, and lighter material properties of polymers that could be printed. Now, AM offers a promising alternative to injection molding and other additive processes.

The most popular and affordable type of AM is known as Fused Deposition Modeling (FDM). These devices utilizes the extrusion of heated thermoplastic filament to build parts one layer at a time. FDM printers are capable of building parts from computer-aided design (CAD) files, however they must first be converted into a format that the printer is capable of reading, such as a .STL file. The .STL files allow the printer to see how the part must be built layer by layer, ensuring the printer is capable of extruding both the part material and any support material (Masood, 2014). Currently within the field of FDM printing, three types of 3D printing devices exist; these are the Cartesian-, Delta-, and Polar-type printers. All utilize filament extrusion to produce parts, however they differ in how they extrude filament, which can lead to numerous differences in print time, print quality, and machine use (3Dnatives, 2018). Cartesian-type printers utilize the cartesian coordinate system to orient the position of the print head and the print bed. Motors allow the print head to move along the X and Z axis, with the print bed moving linearly along the Y axis. This device is capable of producing accurate parts, however print times can be longer relative to other printer types. Delta printers also utilize cartesian coordinates, however these printers have six axis instead of three. They consist of an extruder connected to three triangular points, which can each be independently moved up and down to change the location of the extruder in space. The print bed does not move on a Delta-type printer. These printers are capable of producing parts much faster, however they often sacrifice print quality for the speed at which they are capable of printing.

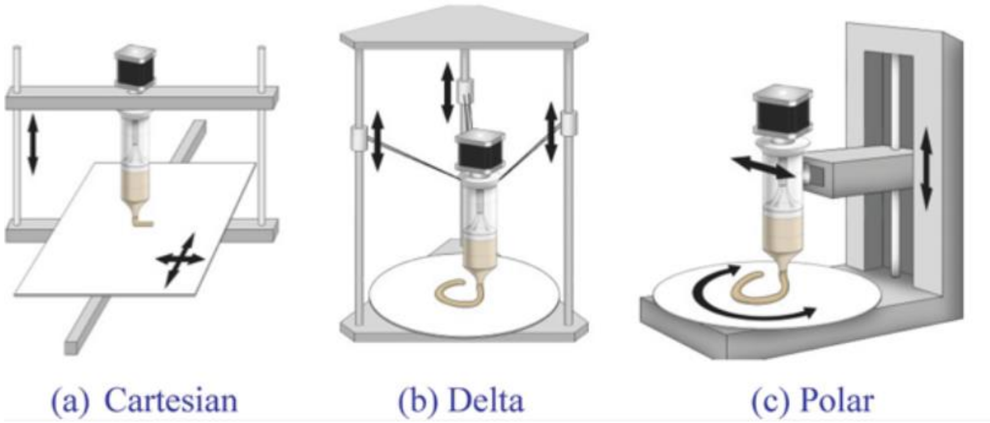


Figure 2.1: The three main types of FDM 3D printers (3D Food Printing, 2018)

Finally, Polar-type printers utilize polar coordinates (angle and distance) instead of the typical X, Y, Z cartesian coordinates. This allows a Polar printer to only need two motors, cutting down on energy usage and the overall printer footprint. The print times are slower than that of a Cartesian-type printer, since they require the printer to do numerous calculations to ensure the printed part is being built correctly (3Dnatives, 2018).

2.2 Creating 3D Printing Filament

The most common material that 3D printers use is a material called polylactic acid (PLA). It is fed into the 3D printer as a long strand of filament that is typically 1.75 mm in diameter. Although 3D printers require PLA, or any other material to be arranged like this, the material must first be put through an extrusion process so that it is compatible, which is usually done by a 3rd party seller. Initially, the source material is stored as pellets so they can be weighed accurately before entering the production process. A computer controlled process dries the source materials to their optimal humidity before they're moved into a mixer. Some producers will add a very precise amount of dye at this point to create different colored filament, yet now the filament is heated and extruded through a calibrated hole, usually 1.75 mm in diameter. Out of the calibrated hole, the filament is fed onto a plastic spool which will then be vacuum sealed and ready for distribution. 3D printers will typically have a spool mounting device along the top rail of their printer that this spool will sit on, and the filament can be fed into the printer's hot end as needed. The feed rate and filament thickness are imperative in the printing process to prevent extruding jams and also maintain a consistent layer application (Lievendag, 2014).

2.3 Molding Bonded Magnets

Traditional permanent magnets are often fragile, brittle, and are limited in the shapes that they can formed. To circumvent some of these shortcomings of permanent magnets, researchers have begun to create bonded magnets with materials like the ones mentioned above, which are fabricated by mixing the magnet powder with a polymer binder (e.g. nylon, epoxy, PLA, etc.), then molded into desired shapes (Li, 2017). These magnets can be molded into shapes through a few different processes: injection molding, compression molding, and extrusion. Bonded magnets that are created through injection molding can be formed into complex shapes and also insert molded directly onto other components to produce assembly parts (China Magnetics). Some of the magnetic powders that are applicable with injection molding are NdFeB, Ferrite, or a combination of the two. Compression bonded magnets offer higher magnetic properties (High energy product up to 12 MGOe) than injection-molded magnets (High energy product up to 6 MGOe), but are limited to more simple geometries (China Magnetics). Magnetic powders that are compatible with compression molding are NdFeB and SmCo, as well as other "rare earth metals."

Some of the advantages of bonded magnets are a relatively powerful magnetic force, a low temperature resistance, a resistance to demagnetization, and a lightweight composition with good mechanical strength. Typical application for bonded magnets are for motors, sensors, and actuators, although they posses a rather low tensile strength and are susceptible to porosity, in which the volume fraction of magnetic powder is around 65% for injection molding and 80% for compression (Li, 2017). Recently, researchers have tried to apply the principle of injection molding to 3D printing, in which a mixture of polymer binder and magnetic powder is extruded through the printer's hot end and layered through the additive manufacturing process. Some of the benefits hoped to be achieved through this process are a reduced amount of material waste, lower energy consumption, reduced labor cost, and a increased production time. Yet some of the shortcomings of recent tests have been a high porosity rate, high melting temperature, different evaporation rates of each of the elements and the complexity in the ternary phase diagram (Li, 2017). It is because of these complexities related to polymer and magnetic properties that have stunted the development of 3D printed magnets.

2.4 Magnetizing Process and Sensitivity to Heat

The most significant limiting factor to the development of 3D printed magnets mentioned above is the magnetic powder's sensitivity to heat. At high enough temperatures, a magnetic material can lose some or all of its magnetic properties. This certainly increases complexity with magnetic powder used for 3D printing, as in order for the printer's polymer filament to be extruded and layered, it has to be heated to temperatures often above 200 degrees C. There are certain stages that a magnetic powder can be heated where its magnetism is not affected, or can be restored when reduced to normal temperatures. The most critical property of a magnetic material is its Curie Temperature, or the temperature at which all magnetization is irreversibly lost. Before the Curie Temperature, a magnet also has a Maximum Operating Temperature, or MaxOpTemp, in which is the temperature limit before irreversible loss occurs (K&J Magnetics). A figure demonstrating this relationship is shown below:

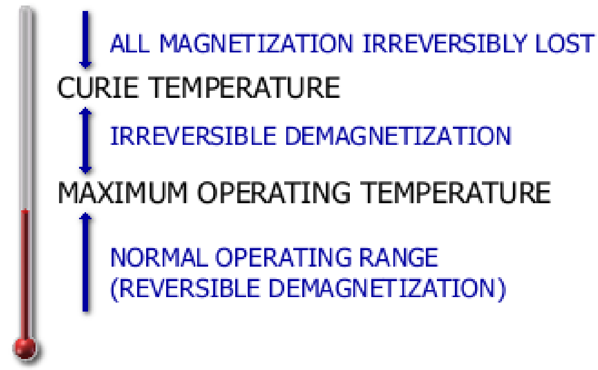


Figure 2.2: Magnetic Temperature Relationships

The term reversible loss refers to some of the magnetic strength lost when a magnet is elevated to higher temperatures (up to MaxOpTemp). When the magnet returns back to room temperature the original strength shall be restored, only when the magnet is at higher temperatures will there be minor strength loss, typically within 5 to 10%. Irreversible loss, occurring when the magnet exceeds the MaxOpTemp, will affect the magnet in which when it returns back to the ambient temperature, some (or all) of the magnet's original strength will be permanently lost. Through the heating process, magnetic strength is a key measure. The product of B times H is often used to describe the strength of magnets (i.e. grade N42 neodymium magnets have a maximum BH (called BHmax) of 42MGOe). This number directly relates to Pull Force Case 1, the attractive force from a single magnet stuck to a large steel plate (K&J Magnetics).

2.5 Properties and Uses of Neodymium

Neodymium was discovered in 1885 by Austrian chemist Carl Auer von Welsbach (Helmenstine, 2014). The discovery was made using a process called fractional crystallization that separated a chemical called didymium into two different brightly colored salts, praseodymium and neodymium. This rare earth metal is most commonly used in an alloy with iron and boron for the purpose of creating extremely powerful permanent magnets (Royal Society of Chemistry, 2018). Since its discovery in 1983, these Neodymium Iron Boron (NdFeB) magnets have made it possible to miniaturize many electronic devices, which has led to modern day mobile phones, loudspeakers, microphones, and many other forms of technology as well.

NdFeB magnets are generally manufactured through the processes of injection molding, compression bonding, and sintering, which is the most common process used for manufacturing NdFeB (Integrated Magnets, 2018). NdFeB can come in the form of solid discs, bars, rings, blocks, and other various shapes. It can also come in powder form in grades ranging from 3330 to 5311. The first two digits in the grade refer to the BHmax (Maximum Energy Product), and the second two digits refer to the intrinsic coercivity, or Hci. These are two of the most common characteristics used to categorize the merit of magnets.

The three most common types of materials used for magnets are NdFeB, Samarium Cobalt, and Ferrite (Constantinides, 2013). At less than -138 degrees celsius and above 180 degrees celsius, NdFeB begins to lose its magnetic characteristics. At those extreme temperatures samarium cobalt becomes the material of choice for permanent magnets. That being said, the reason why NdFeB is the prefered type of material for permanent magnets is because it is widely abundant, available at moderate to low prices, and has the highest magnetic output of the three materials.

2.6 Properties of Polylactic Acid and Other 3D Printable Plastics

Polylactic acid (PLA) fibers are made using lactic acid as the basis for manufacturing (American Fiber Manufacturers, 2017). This lactic acid comes from fermenting natural sugars from plant such as corn or sugar beets. As a result, PLA does not emit the typical smell that most petroleum based plastics do, and is also biodegradable. PLA is made primarily through two different processes, polymerization and condensation (Rogers. 2015). Ring-opening polymerization is particularly common and involves metal catalysts mixed with lactide to create larger PLA molecules. The condensation process for manufacturing PLA is similar, however, the difference is the temperature used and the condensates that are byproducts of the reaction. PLA is classified as a thermoplastic polyester. Thermoplastics generally become liquid at their melting point, which for PLA is between 150 to 160 degrees celsius. One characteristic of thermoplastics that is particularly useful for 3D printing is the ability to be heated to its melting point, cooled, and reheated without major damage or degradation (Rogers. 2015).

The two main types of plastics used for FDM printing are PLA and another type of thermoplastic called Acylonitrile Butadiene Styrene (ABS). ABS is an extremely sturdy plastic that is widely used in industry for plastic car parts, musical instruments and even legos (Hesse, 2015). However, the reason why ABS isn’t more commonly used is because it requires a heated print bed which most low cost printers do not have. ABS also emits toxic fumes when heated during the printing process and requires proper ventilation. For these reasons many hobbyists and schools elect to use PLA. PLA also has higher printing speeds, lower layer heights, sharper printed corners, and lower potential for warping of parts (iGEM, 2015).

Although PLA and ABS are the two most common types of material used for 3D printing, Nylon is also used occasionally. 3D printed Nylon is extremely strong and durable in addition to having a high melting temperature (Matterhackers, 2014). These qualities make it ideal for mechanical or functional parts like hinges or gears. Although Nylon can be a very versatile material for 3D printing one major drawback is that it can readily absorb water from the air. This means that while 3D printing water in the nylon filament can explode causing air bubbles and decreasing adhesion. This can weaken the overall strength of the part and ruin the finish. In order to dry nylon filament to prevent this, it can be placed in an oven at 160 to 180 degrees Farenheit for six to eight hours.

2.7 3D Printing Permanent Magnets

Until the past few years there has been very little research performed on 3D printing permanent magnets. In 2017 Professor Christian Huber at the University of Vienna in Austria published a paper on 3D printing polymer-bonded rare-earth magnets. Huber manufactured his own polymer-bonded magnetic filament which consisted of polyamide 12 (PA12, also known as Nylon 12) purchased from Polyking and magnetic isotropic MQP-S-11-9 NdFeB powder purchased from Magnequench Corporation (Huber et. al, 2017). These materials were then mixed and extruded into filaments composed of 85 percent weight (wt%) MQP-S-11-9 powder and 15 wt% PA12 using a Leistritz ZSE 18 HPe-48D twin-screw extruder. The extruded filament had a standard diameter of 1.75 millimeters and was placed on a spool of .5 meters to prevent breaking the brittle filament. The magnets were printed by a widely available low cost FDM 3D printer from Code P. During the printing process magnetization was performed using a self-built water-cooled electromagnet that was able to produce a maximum magnetic flux density of 1.9 teslas (Huber et. al, 2017). To determine the magnetic properties of the printed magnets a stray field measurement was performed using a 3D Hall Sensor purchased from Infineon. Huber was able to successfully print permanent 3D magnets with specific stray field distributions and magnetic properties that could be used for a wide variety of applications. The only limitations were that printing was only possible in the z direction and the unevenly manufactured filament led to uneven prints.

Researchers from the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee have also been working on developing methods for 3D printing magnets. In this study, Big Area Additive Manufacturing (BAAM). BAAM is a 3D printing method developed specifically by ORNL that allows for the printing of large scale parts (Li et. al, 2016). ORNL utilized MQP B+ NdFeB powder also from Magnequench as well as Nylon-12 for their magnetic compound. Their composition, however, was slightly different than the one Huber and his team used. ORNL used 65 percent weight MQP B+ powder and 35 percent weight Nylon 12. The compound was then mixed in an extruder to make pellets. An advantage of the BAAM over the low cost printer that Huber used is that the BAAM does not require prefabricated filament and so the extruded pellets were able to be fed into the BAAM directly. ORNL did not include any information in their publication on any magnetization process or method of measuring magnetic properties. They did however, present their results comparing printed magnets to injection molded magnets. It was found that injection molded magnets and printed magnets had very similar capabilities, with printed magnets having a slight advantage in weight in cost. That being said sintered NdFeB magnets still have a much “higher energy product [and] higher tensile strength” according to the ORNL (Li et. al, 2016).

3. 3D Printer

The decision was made to design and build a 3D printer from scratch so that it could be modified and redesigned if need be for the sake of attaching the solenoid and printing with the NdFeB PA-12 filament. One concern was that a 3D Printer such as an Ultimaker or Prusa would be difficult to modify. The entire bill of materials for the 3D printer is included in Appendix A for reference. Since the team designed this printer themselves, there were certain aspects of the printer that had to be iterated and redesigned multiple times. One example of this was the brackets that held the smooth rods in place. Since they were made of PLA the deformed when placed under the stress of the operating printer. They were redesigned multiple times to reduce deformation.

3.1 Assembly Process

This chapter provides an overview of the process for building the 3D printer, descriptions of the significance of major parts, and the step-by-step assembly of the 3D printer. Overall, there are nine sections each with the necessary tools and parts required for the section, a short description of the section, and step-by-step descriptions with corresponding visuals. This chapter is based on the manual that one of the group members of the MQP team made for their Professional Writing MQP. The purpose of this chapter is to clearly show the logic behind the design choices that were made for the 3D printer as well as the step-by-step build process that future MQP groups can reference if they are also building a 3D printer.

PROCESS OVERVIEW

Chapter 2

The heatbed is the surface that plastic is extruded onto. It is crucial because when extruded plastic is cooling it will warp on the edges if it does not cool and shrink evenly.

Chapter 3

The frame base provides structure for the HeatBed Assembly and the XZ frame. It is made up of four 12-inch pieces of 8020 aluminum stock.

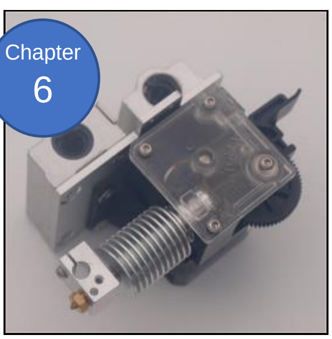
Chapter 4

This frame is crucial to the overall integrity of the machine since it supports the vertical smooth and threaded rods that drive the extruder up, down left, and right, and the carriages that guide the smooth and threaded rods.

Chapter 5

5 NEMA 17 Motors are used on this 3D printer to drive the heatbed back and forth, as well as to move the extruder up and down.

Chapter 6

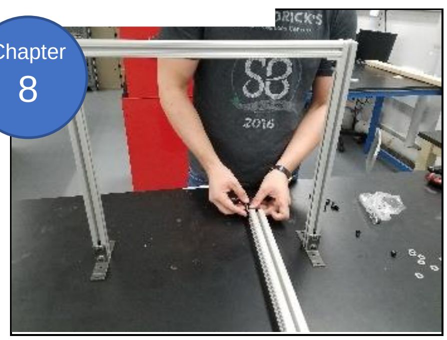


The extruder itself is what lays down heated plastic material on to the heatbed layer by layer to create 3D objects.

Chapter 7

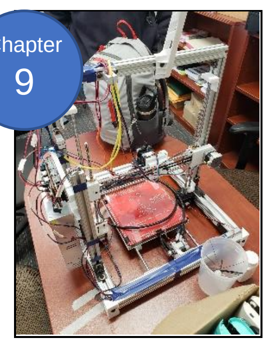
The XZ and X carriages hold the smooth and threaded rods in place, as well as the pulleys that much of the movement of the machine relies on.

Chapter 8



The cross bar attaches across the top of the two pieces of the XZ frame. The main purpose of the cross bar is to ensure that the two pieces of the XZ frame do not bow inward due to resulting forces of the machine running.

Chapter 9



The power supply is 12 volt and supplies energy to the Arduino Board, NEMA Motors, heatbed, and extruder.

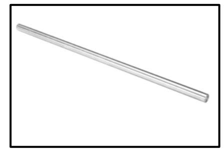
Heatbed Assembly

Required Parts

4x WINSINN Leveling Spring M3 Screw Knobs

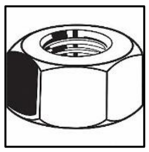
PCB Heatbed

4x LM8UU Bearings

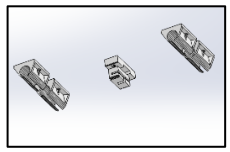


8mm Diameter Smooth Rods

8x M3 (3 Millimeter) Nuts



8x M3 Nuts



3D Printed Bearing Holders and Belt Holder

Heatbed Mount Plate for Bearings and Smooth Rods

Required Tools

Metric Thread Tap Kit

Epoxy

M3 Hex Key

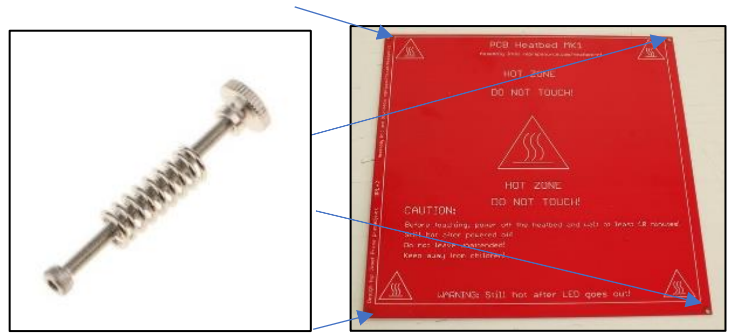
The heatbed is the surface that plastic is extruded onto. It is crucial because, when extruded plastic is cooling, it will warp on the edges if it does not cool and shrink evenly. The heatbed supplies a consistent and evenly distributed temperature for parts to cool on. The heatbed itself is aluminum because of its desirable thermal conductance properties, which ensure even heat distribution. It is heated by a thermistor, which is connected to the 12-volt power supply.

Steps

1. Attaching the Heatbed to the Aluminum Plate

The heatbed is attached to the aluminum plate using level spring screw knobs that allow the level of the heatbed to be changed at each corner.

1. Attach the heatbed on top of the aluminum plate using WINSINN Leveling Spring M3 Screw Knobs. There are four holes at each of the corners of the heatbed and aluminum plate. Each of the four screw knobs should be inserted through each corner hole to connect the two plates.

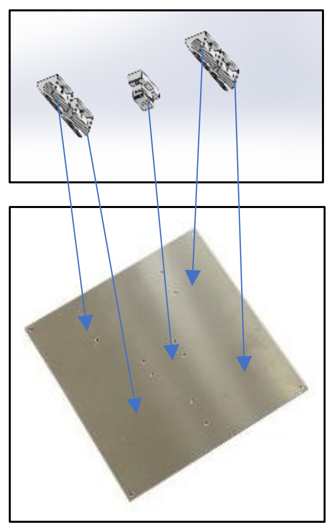


2. Attaching the Bearing Holders and Belt Holder to the Aluminum Plate

The bearing holders hold LM8UU bearings that the smooth rods slide through. The belt holder holds the end of the belt allowing a loop to be formed around the NEMA motor so the heatbed can move back and forth.

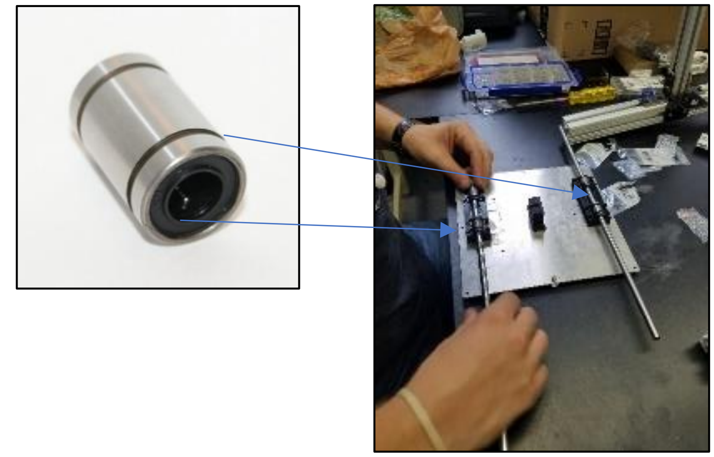
1. Attach the four 3D printed bearing holders to their corresponding holes on the aluminum plate using M3 screws and nuts.

   Note: If for some reason the aluminum plate does not come with holes already tapped, the hand tapping kit can be used to tap holes or epoxy can be used to attach the smooth rod and belt holders.



2. Attach the belt holder in between the 3D printed bearing holders. Attach using one of the two methods mentioned in the previous step.

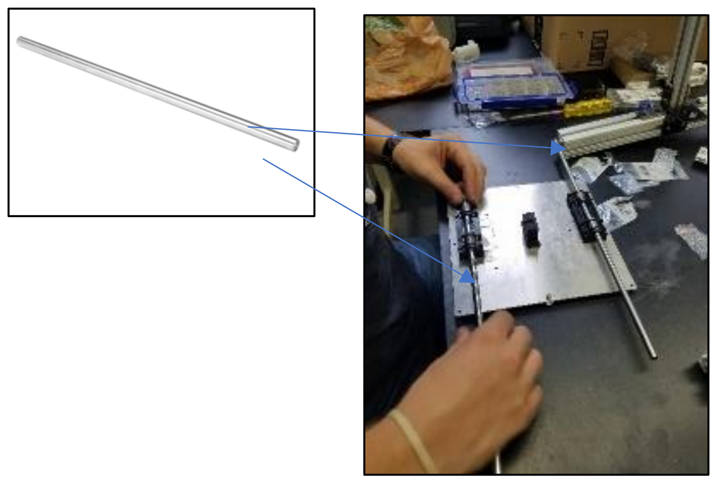
3. **Inserting the Bearings**



Four LM8UU bearings are inserted into the 3D printed bearing holders. The smooth rods are then slid into the bearings. There should be little to no friction and the rods should be able to slide back and forth easily in the bearing.

1. Insert the bearings into the bearing holders. The bearings should fit snug in the holders; however, if they are sliding back and forth, they can be held in place with epoxy.

4. **Inserting the Smooth Rods**



The smooth rods allow the heatbed to move back and forth.

1. Insert the two smooth rods through the pairs of bearing holders on either side of the aluminum plate. The rods should be to able slide easily in the bearings.

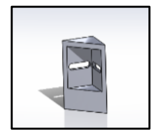
Frame Base Assembly

Required Parts

30x ¼-20 Inch Screw with Standard T Nut

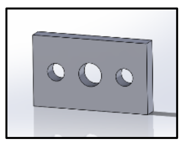
4x Hole Inside Corner Gusset Corner Bracket

4x 12-Inch Aluminum 80/20 Stock

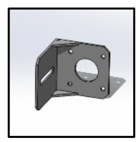


4x 3D Printed Frame Base Feet

Assembled Heatbed (from last step)

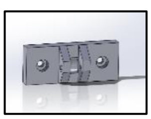


4x 3D printed smooth rod holders



1x 3D Printed NEMA Motor Mount for Y Movement

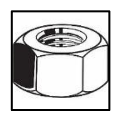
2x NEMA Motor Mounts for Z Movement



3D Printed Y Movement Pulley Mount

GT2 3mm Bore Aluminum Toothless Timing Belt Idler Pulley

1x M3 Screws



1x M3 Nut

Required Tools

¼-20-inch Hex Key

The frame base provides structure for the Heatbed Assembly and the XZ frame. It is made up of four 12-inch pieces of 8020 aluminum stock. The 8020 aluminum stock is slotted and allows for

L brackets and other various mounts to be attached to the base using screws and T nuts. The 3D printed feet provide increased stability when the machine runs and lifts it above the surface it is operating on.

Steps

1. Attaching the Y NEMA Motor Mount

The Y NEMA Motor mount supports the Y NEMA motor. It should be attached in the center of a 12-inch-long piece of aluminum 8020 stock.

1. Attach the 3D Printed NEMA Motor mount for Y Movement to the center of 1 Piece of aluminum 80/20 stock using ¼-20 screws and T nuts.

2. Attaching the Smooth Rod Mounts

The smooth rod mounts hold the smooth rods and heatbed in place. The mounts use a press fit design, so the rods fit snuggly in the mounts and do not move.

1. Attach two 3D printed smooth rod mounts exactly 2 inches from either side of the NEMA motor mount for the Y movement. Use ¼-20-inch screws and T nuts for this task.

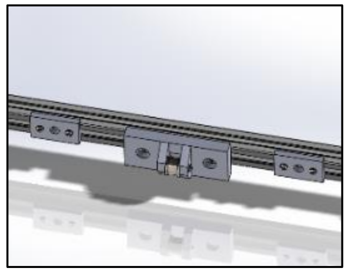
3. Attaching the Z NEMA Motor Mounts

The two Z NEMA motor mounts support the two NEMA motors required to move the extruder up and down in the Z direction.

1. Attach the 2 NEMA Motor mount for Z movement in the center of two of the remaining pieces of aluminum 80/20 using the same screws and T nuts used in the previous step.

   Note: The orientation of these mounts is different than the one in the previous step.

4. Attaching the Smooth Rod Mounts and Pulley Mount



The last piece of aluminum 8020 stock that has not been altered will be used for the 3D printed Y movement pulley mount and opposing smooth rod holders. The pulley and pulley mount are for the belt that drives the heatbed back and forth in the Y direction.

1. Attach the 3D printed pulley holder in the center of 12-inch-long piece of aluminum 8020 stock. Use ¼-20-inch screws and standard T nuts.
2. Place the GT2 Smooth Pulley in the center of the pulley mount. Slide an M3 Screw through the hole in the pulley and secure it on the other side with the M3 nut.
3. The 2 remaining smooth rod holders should be installed on either side of the pulley holder, exactly parallel with the two on the opposite piece of stock. Use ¼-20 inch screws and standard T nuts.

XZ Frame and Full Frame Assembly

Required Parts

24x ¼-20 Inch Screw with Standard T Nut

6x Hole Inside Corner Gusset Corner Bracket

3x 12 Inch Aluminum 20/20 Stock

Required Tools

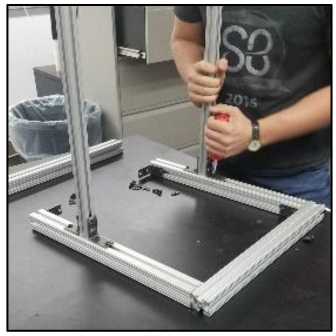
¼-20-Inch Hex Key

The XZ frame is made up of two pieces of aluminum 2020 stock. This frame is crucial to the overall integrity of the machine since it supports the vertical smooth and threaded rods that drive the extruder up, down, left, and right, and the carriages that guide the smooth and threaded rods. If the XZ frame is not carefully measured and installed it can adversely affect the functionality of the entire printer. Once the XZ frame is attached the rest of the base frame can be assemble and the entirety of the frame, aside from the cross bar, is completed.

Steps

1. Assembling the XZ Frame

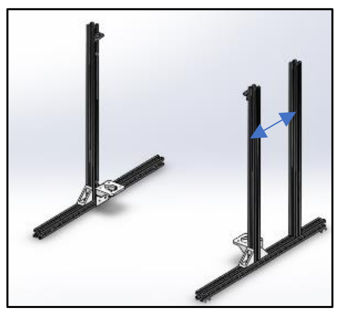
The XZ frame provides support for the smooth rods, threaded rods, and the carriages that hold them. It is crucial to the structural integrity of the printer.



1. Attach two of the aluminum 2020 pieces of stock, standing vertically, adjacent to the center of the NEMA Motor mounts for Z movement on each side of the frame. Use the L brackets, ¼-20 inch screws, and standard T nuts to attach these pieces to the frame base.

2. Attaching the Last Piece of Aluminum 2020 Stock

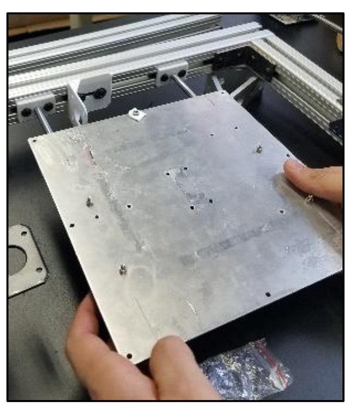
The third piece of aluminum 2020 stock allows for the power supply and Arduino board to be mounted in between the two pieces of stock.



1. Attach the third piece of aluminum 2020 in line with either of the other two pieces approximately 5.5 inches apart from their center slots. Attach using L brackets, ¼-20 inch screws, and standard T nuts.

3. Installing the Heatbed

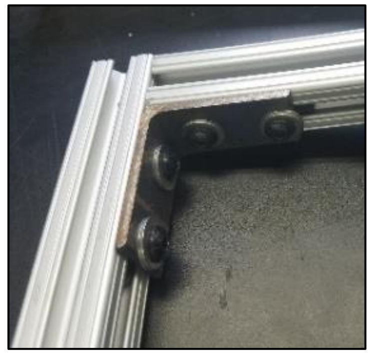
The smooth rods should fit snugly into the smooth rod holders and the heatbed sit in the center of the frame base.



1. Press the same end of the two smooth rods into one set of the smooth rod holders.
2. Press the other end of the two smooth rods into the other set of the smooth rod holders. The heatbed should be suspended roughly two inches off the ground and should be able to slide back and forth smoothly.

4. Connecting the Frame Base

Prior to this step the frame base was still in pieces. Once it is all attached the frame base should form a square.

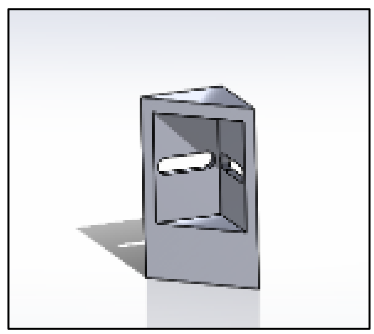


1. Attach the 4 pieces of 8020 stock at the corners in order to make the frame base into a square. Each piece should be connected at the corners using L brackets, ¼-20 screws, and standard T nuts.

   Note: The heatbed displayed in the SolidWorks screenshot is only meant to show positioning, it is not an accurate visual representation of the heatbed.

5. Attaching the Feet

The 3D printed feet of the printer elevate it off the ground and ensure that it sits level on whatever surface it is used on. They also serve to minimize vibration while printing for better quality prints.



1. Attach the 4 3D printed feet to each of the corners of the frame base. Use one ¼-20 screw and T nut for each foot.

Y & Z NEMA Motors Installation

Required Parts

3x NEMA 17 Motors

2x 5x8mm Aluminum Flexible Shaft Coupler

2x GT-2 Teeth Timing Pulley

12x M3 Screw

12x M3 Nut

2-meter-Long GT-2 Timing Belt

24x ¼-20 Inch x 3/4 Screw with Standard T Nut

Required Tools

¼-20-Inch Hex Key

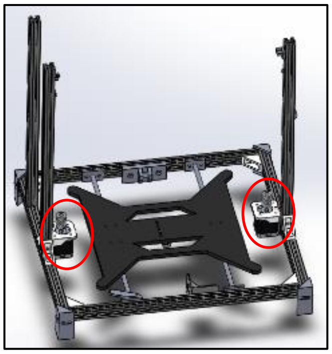
Scissors

5 NEMA 17 Motors are used on this 3D printer to drive the heatbed back and forth, as well as to move the extruder up and down. The two NEMA motors that are mounted adjacent to the XZ frame turn the threaded screw to move the extruder up and down. The rest of the NEMA motors rely on a pulley system using belts that loop around the toothed pulley that attaches to the NEMA motors and loop around smooth pullies on the opposite side. This includes the NEMA motor mounted offset from the center of the heatbed that moves it back and forth in the Y direction and the NEMA motor mounted on the XZ carriage that moves the Extruder back and forth in the X direction.

Steps

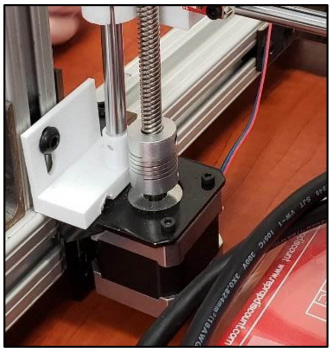
1. Attaching the Z Movement NEMA Motors

The Z Movement NEMA Motors are responsible for moving the extruder up and down.



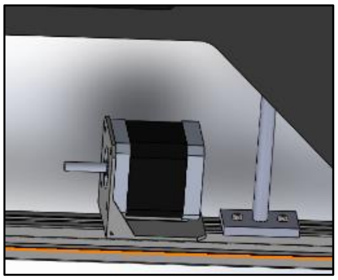
1. Attach one of the Z NEMA motors to one of the two Z NEMA motor mounts on either side of the heatbed. Use M3 screws.
2. Attach the second Z NEMA motor to the remaining Z motor mount on the opposite side of the heatbed. Use M3 screws.

2. Attaching the NEMA Motor Couplers



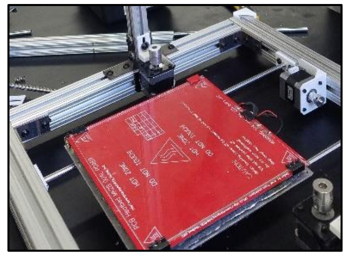
1. The coupler serves as the holder for the threaded lead screw that the NEMA motors turns. This screw is responsible for moving the 3D printed XZ carriages up and down.
2. Push the one of the couplers onto the tip of one of the Z NEMA motors. The coupler should fit snuggly.
3. Repeat this step for the remaining Z NEMA Motor.

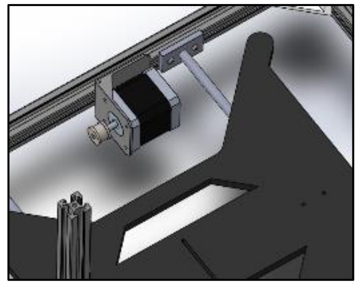
3. Attaching the Y Movement NEMA Motor



This NEMA motor is responsible for moving the heatbed back and forth in the Y direction. Instead of a coupler, a GT2 pulley with teeth is pressed on the end of the NEMA motor, for the belt to be looped around.

1. Attach the Y NEMA motor to the mount offset from the center of the heatbed. Use M3 screws.

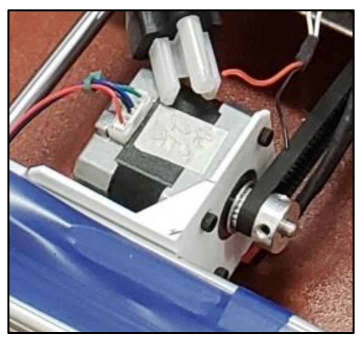




4. Attaching GT2 Teeth Timing Pulley

The GT2 teeth timing pulley fits on the end of the Y movement NEMA motor. The teeth allow the timing belt to loop around it and prevent slipping.

1. Press the GT2 teeth pulley on to the top of the Y direction NEMA motor.



5. Attaching GT2 Y Movement Timing Belt

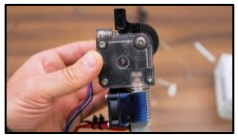
The GT2 Timing Belt loops around the GT2 teeth pulley at the end of the Y NEMA motor, around the smooth pulley on the opposite side of the heatbed and attaches to the belt holder on the bottom of the heatbed.

1. Cut a foot-length piece from the 2-meter timing belt using scissors.
2. Loop the belt around the smooth pulley and the GT2 teeth pulley, fastening it to the belt holder underneath the heatbed so the teeth on the belt catch the teeth of the belt holder.

XYZ Movement Installation

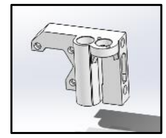
Required Parts

2x NEMA 17 Motors



2x E3D V6 Titan Extruder Kit

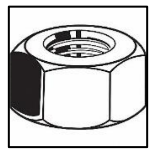
8x M3 Screws



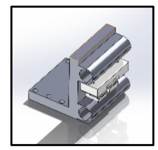
3D Printed Z Movement Bracket Left Side

8x M3 Nut

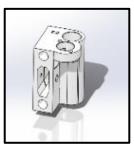
LM8UU Bearings



M8 Nuts



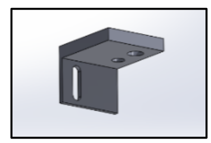
3D Printer Extruder Carriage



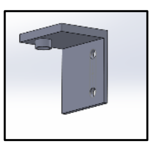
3D Printed Z Movement Bracket Right Side

2x Smooth Rods

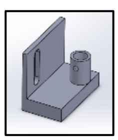
3D printed Belt Holder



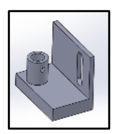
Top Smooth Rod Holders Left Side



Top Smooth Rod Holders Right Side



Bottom Smooth Rod Holder Left Side

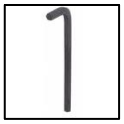


Bottom Smooth Rod Holder Right Side

4x ¼-20 Inch Screw with Standard T Nut

2x Threaded Rods with Flange

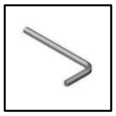
Required Tools



¼-20-Inch Hex Key

2.5mm Hex Key

Pozidriv Screw Driver



M8 Hex Key

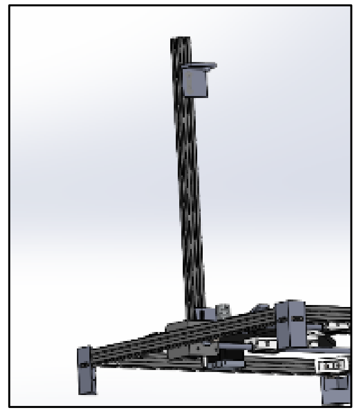
M3 Hex Key

Epoxy

The XZ and X carriages hold the smooth and threaded rods in place, as well as the pulleys that much of the movement of the machine relies on. The extruder mounts to the X carriage which holds the smooth rods and pulley in place that allow the extruder to move back and forth. The carriages are all 3D printed so it is ideal to use ABS and a high-quality printer in order to ensure strength and lack of warping in the parts. If any of the carriages are warped, then the bearings that go inside of the carriages for smooth rods may not fit properly and hinder the mobility of the machine. The extruder itself is what lays down heated plastic material on to the heatbed layer by layer to create 3D objects. The extruder is mounted to a 3D printed carriage which is driven back and forth on smooth rods by the NEMA motors and pulleys. The extruder is made up of a heat sink, heating block, brass nozzle extruder, a fan, and a thermistor. The heating block heats up the plastic before extrusion and the heat sink above it prevents heat from traveling up the extruder and prematurely melting the filament.

Steps

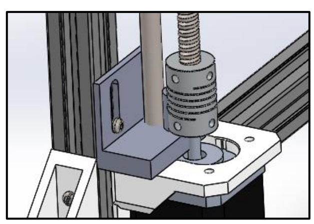
1. Attaching Top Smooth Rod Holders



The top smooth rod holders hold the smooth rods that the XZ carriages move up and down on in the Z direction.

1. Attach one of the 3D printed top smooth rod holders two inches from the top of one of the sides of the XZ frame. Use ¼-20 screws and standard T nuts.
2. Attach the second top smooth rod holder to the other side of the XZ frame. Use ¼-20 inch screws and standard T nuts.

2. Attaching Bottom Smooth Rod Holders



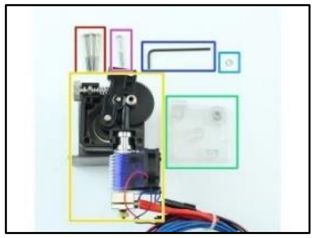
The bottom smooth rod holders hold the smooth rods that the XZ carriages move up and down on in the Z direction.

1. Attach one of the 3D printed bottom smooth rod holders two inches from the top of one of the sides of the XZ frame. Use ¼-20 screws and standard T nuts.
2. Attach the second bottom smooth rod holder to the other side of the XZ frame. Use ¼-20

inch screws and standard T nuts.

3. Assembling E3D V6 Titan Extruder Kit

The E3D V6 Titan Extruder V6 Kit holds the heat sink and extruder itself and provides a mode of feeding filament into the extruder itself, as seen in the yellow box.

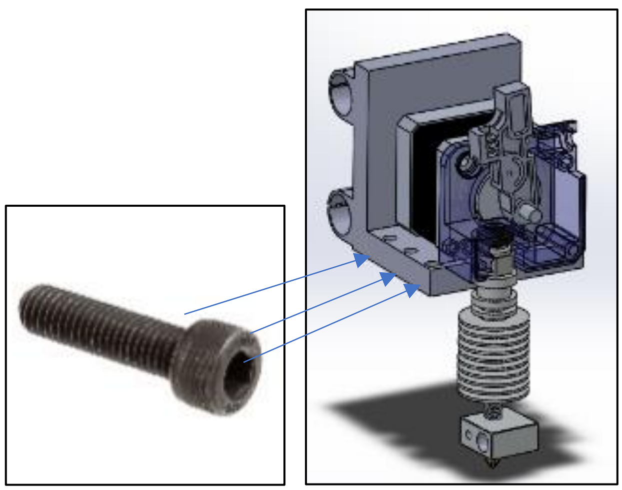


e3d-online.dozuki.com/Guide/1.75mm+Direct+Titan+Assembly/19?lang=en

1. Follow the guide at this link for manufacturer provided instructions on how to assemble the kit.

4. Attaching the E3D V6 Titan Extruder Kit to the 3D Printed Extruder Carriage

The 3D printed extruder carriage holds the E3D V6 Titan Extruder Kit and has holders for LM8UU bearings on the back side.



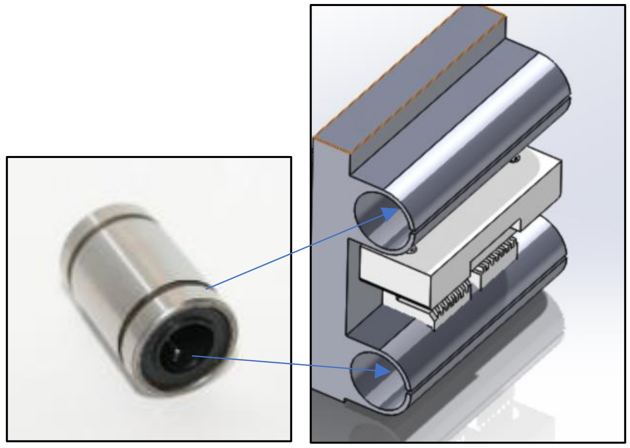
1. Attach the E3D V6 Titan Extruder Kit to the 3D printed extruder carriage using M3 screws and nuts.

5. Attaching the Extruder Carriage Belt Holder

The belt holder on the back of the extruder carriage is responsible for holding the GT2 belt that controls the X direction movement of the extruder.

1. Insert LM8UU bearings into the back of the carriage.

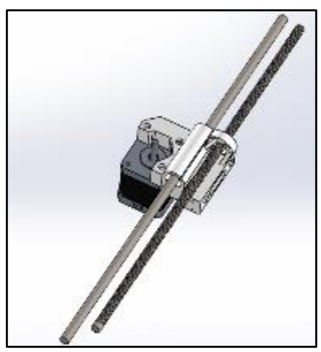
   Note: If the bearings fall out or move inside the carriage, glue can be used on the bearings to keep them in place.



2. Once the bearings are in place the belt holder can be attached to the back of the carriage using epoxy.

6. Attaching the Left Z Movement Bracket

The Left Z Movement bracket houses the bearing, smooth rod, threaded lead screw, and X NEMA motor.



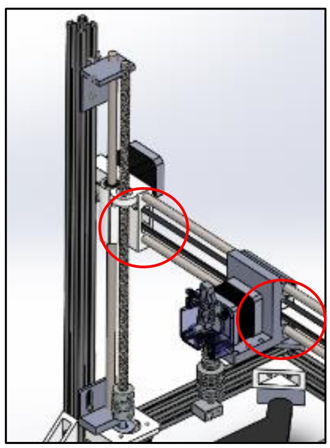
1. Insert one LM8UU bearing into the left Z movement bracket.
2. Attach one of the NEMA motors to the outer portion of the bracket using M3 screws and nuts.
3. Insert one smooth rod through the bearing.
4. Attach the threaded rod using the threaded rod, flange, and M3 screws and nuts.

7. Inserting the Smooth and Threaded Rods

The smooth and threaded rods move the left Z bracket up and down. They also keep the bracket parallel with the XZ frame.

1. Once the left Z movement bracket is assembled, the smooth rod should be inserted into the smooth rod holders and the threaded rod should be inserted into the NEMA Motor Coupler.

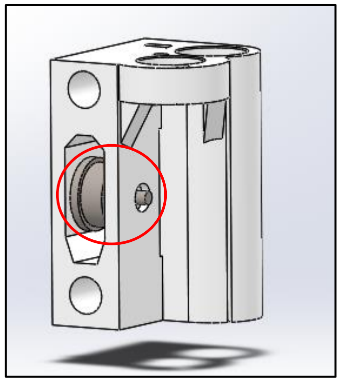
8. Attaching X Movement Smooth Rods



Two smooth rods should be inserted horizontally in the back of the 3D printed extruder carriage. Those smooth rods should then be slid into the left Z movement bracket.

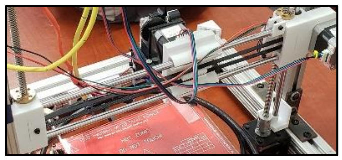
1. Insert the first smooth rod into the top bearing on the extruder carriage and the top hole in the left Z movement bracket.
2. Insert the second smooth rod into the bottom bearing on the extruder carriage and the bottom hole in the left Z movement bracket.

9. Attaching the Right Z Movement Bracket



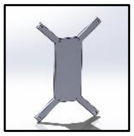
Repeat steps 1-7 on the opposite side of the machine.

1. Insert the smooth pulley for the X movement into the right Z movement bracket using an M3 screw and nut.
2. Loop the timing belt around the smooth pulley and the GT2 teeth pulley on the NEMA motor in the left Z movement bracket. Fasten it to the belt holder on the back of the extruder carriage, similarly to the heatbed.



Power Supply and Arduino Board Installation

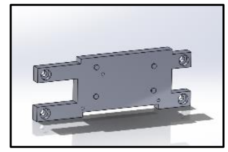
Required Parts



3D Printed Power Supply Mount

12 V Power Cord

8x ¼-20 Inch Screws and Standard T Nut



3D Printed Arduino Board Mount

ACER Racing Superworm Silicone Wire 14 Gauge 10' Copper Wire Very Flexible 14 AWG 400 strands

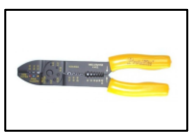
RAMPS 1.4

Arduino Mega 2560

12 Volt Power Supply

Required Tools

¼-20-inch Hex Key



Wire Cutters

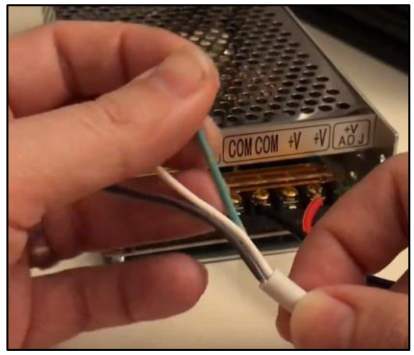
Cross Point Screw Driver

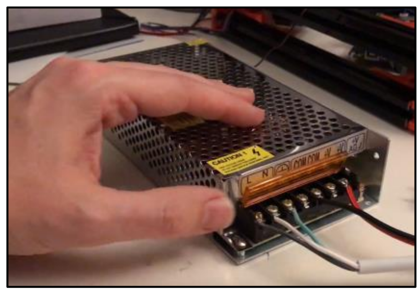
The power supply is 12 volt and supplies energy to the Arduino Board, NEMA Motors, heatbed, and extruder. This power supply is mounted to the one piece of the XZ frame and an additional vertical piece of aluminum 2020 installed adjacent to it. The mount is almost an "x" shape between the two pieces. In order to get power to the power supply, an average 12 volt power cord, should be stripped attached and the individual hot, neutral, and ground wires should be connected to their marked corresponding inputs in the power supply.

Steps

1. Connecting the Power Cord to the Power Supply

A normal 12 V power cord will be cut, stripped, and wrapped around the screws of the power supply. The male end will be plugged directly into the wall to provide power to the power supply.





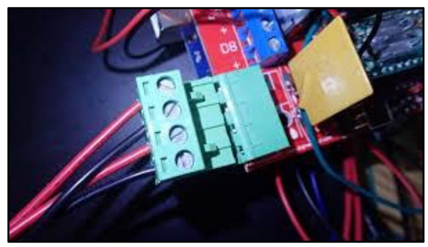
1. Cut the female side of the power cord so the male side can still be plugged in.
2. On the cut side strip the three wires using the wire stripper tool. There should be three exposed wires: green, black, and white.
3. The black wire should go to the screw marked with the "L".
4. The white wire goes to the Neutral screw marked "N" in the middle. and
5. The green ground wire goes to the "_|_" symbol.
6. Loosened each screw with the cross-point screw driver.
7. Wrap the copper threads of each wire as tightly as possible around the base of the screw.
8. Re-tighten the screw.

2. Connecting the Power Supply to the RAMPS 1.4 Board

Using the 14 gauge wire, the power supply will be connected to the RAMPS 1.4 board. This will supply the RAMPS 1.4 board with power and will allow for different components of the printer such as motors and endstops to be connected.

1. Connect two of the black ends of 14-gauge wire to the two adjacent COM ports on the power supply.

   Note: The wires should be attached to the power supply by loosening and tightening the screws just as in Step 1.
2. Connect two of the red ends of the 14-gauge wire to the two adjacent +V ports on the power supply.
3. Connect these wires to the port on the RAMPS 1.4 board in order from top to bottom of red, black, red, black.



3. Mounting the Power Supply

Using the 3D printed mount, mount the power supply in between the adjacent pieces of aluminum 2020 stock.

1. Attach the power supply to the 3D printed mount using M3 screws nuts.
2. Once the Power Supply is attached to the mount, use ¼-20 screws and standard T nuts in the corner holes of the 3D printed mount to attach the power supply in between the two pieces of vertical aluminum 2020 stock.

4. Mounting the Arduino and RAMPS 1.4 Boards

Using the 3D printed mount, mount the Arduino and RAMPS 1.4 Board in between the adjacent pieces of aluminum 2020 stock, directly above the power supply.

1. Attach the Arduino Board and RAMPS 1.4 to the 3D printed Arduino Board mount using M3 screws and nuts.
2. Attach the mount directly above the power supply using ¼-20 screws and standard T nuts in the corner holes of mount.

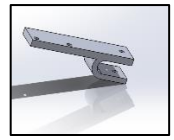
Crossbar and EndStop Assembly

Required Parts

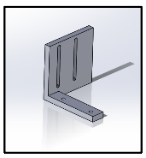
2x L Brackets

1x Aluminum 2020 Stock

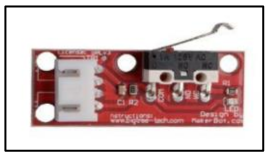
2x ¼-20 Inch Screws and Standard T Nut



3x 3D Printed X/Y Movement Endstop Mount



3D Printed Z Movement Endstop Mount



3x Endstop

12x M3 Screws

Required Tools

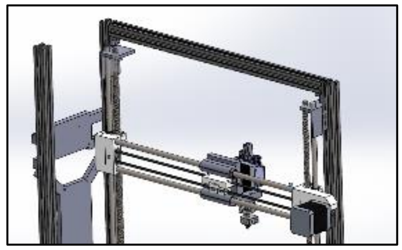
¼-20 Inch Hex Key

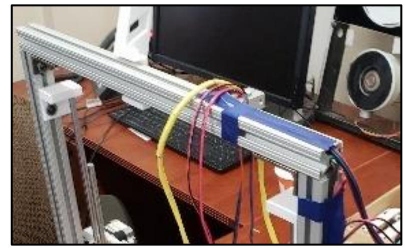
M3 Hex Key

The cross bar is the piece of aluminum 2020 stock that connects the two vertical pieces of the XZ frame. The main purpose of the cross bar is to ensure that the two pieces of the XZ frame do not bow inward due to resulting forces of the machine running. The cross bar attaches across the top of the two pieces of the XZ frame. The cross bar is also aluminum 2020 stock and allows for a 3D printed filament spool holder to be attached. The purpose of the endstop is to alert the printer to stop once the extruder or heatbed runs into it in either x, y, or z direction.

Steps

1. Attaching the Cross Bar

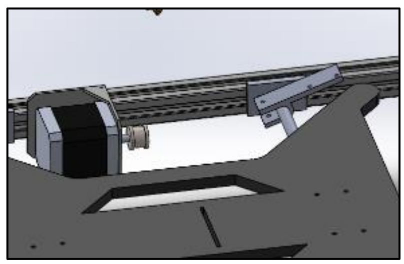




The aluminum 2020 cross bar provides structure to the rest of the frame and ensures that the two pieces of stock on the XZ frame are parallel.

1. Attach an aluminum 2020 piece of stock to the top of the two vertical aluminum 2020 pieces of stock. Use M8 Screws, L brackets, and T nuts.

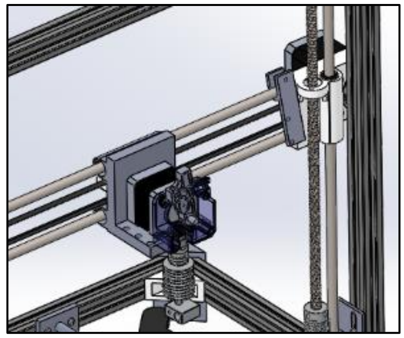
2. Attaching the Y Endstop

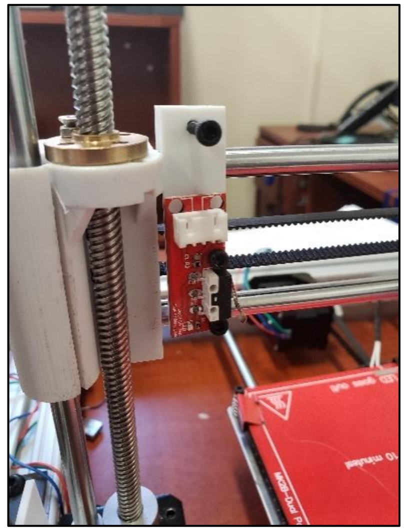


The Y endstop prevents the heatbed from running into the NEMA motor or frame. Once the heatbed touches the endstop it stops and returns to its original position.

1. Attach one of the three endstops to the Y endstop mount. Use M3 Screws and nuts.
2. Attach the endstop and mount to the smooth rod closest to the tip of the Y NEMA motor. Use an M3 screw and nut.

3. Attaching the X Endstop

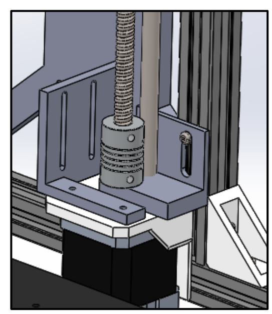




The X endstop determines the parameters the extruder can move in the X direction and prevents it from crashing into the carriages.

1. Attach one of the endstops to an endstop mount using M3 screws and nuts.
2. Attach the endstop and mount to the upper smooth rod using an M3 screw and nut.

4. Attaching the Z Endstop



The Z endstop determines the parameters the extruder can move in the Z direction and prevents the nozzle from crashing into the heatbed.

1. First attach the endstop to the Z endstop mount using two M3 screws and nuts through the two slots in the mount.
2. Attach the mount on top of the NEMA motor using the NEMA motor mount screws that are already there.

Arduino and RAMPS 1.4 Boards Wiring

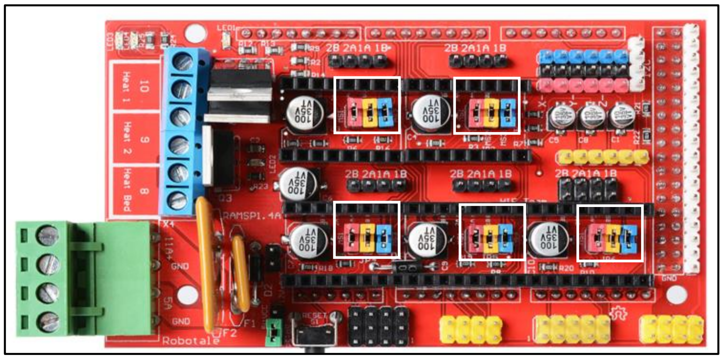
Required Parts

			
5x UEETEK Stepper Motor Cables	3x Endstop Wires	Arduino Mega 2560	RAMPS 1.4 Board
			
5x Stepper Driver	LCD Smart Display Controller		

The Arduino board is the motherboard of the printer and controls the movement of the NEMA motors, the thermistors, and the extruder fan. However, the cables from all of these elements do not plug directly into the Arduino board itself. They plug into a RAMPS 1.4 board that is just a board that connects to the Arduino board that offers more inputs and can receive signals from the code uploaded to the Arduino board. The RAMPS 1.4 board also has ports that connect directly to the power supply, and in turn supplies power to the motors and thermistors.

Steps

1. Installing the Stepper Drivers

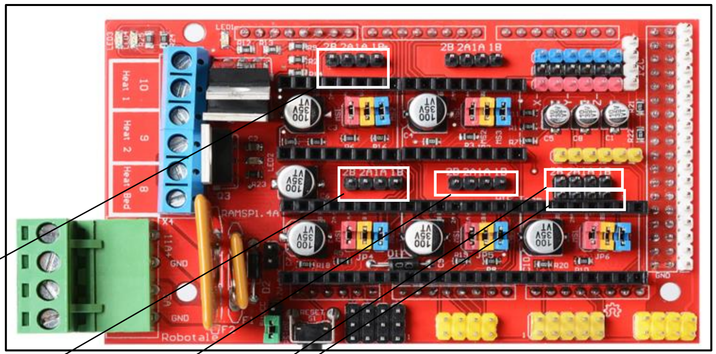


The stepper drivers control the coils in the stepper motors, causing them to trigger and rotate the motor precisely.

1. Install the five stepper drivers to their corresponding sets of pins.

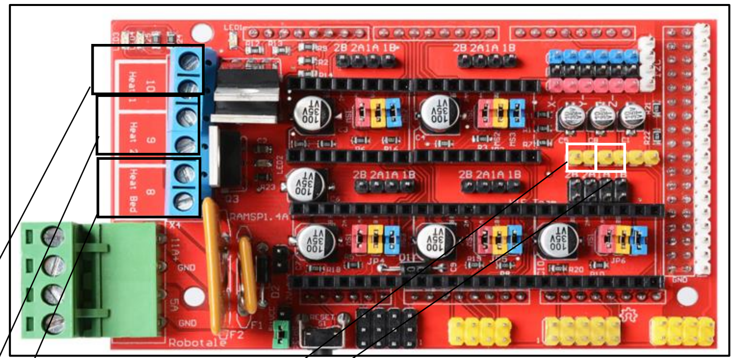
2. Plugging in the NEMA Motors

The X, Y, Z, and Extruder NEMA motors should be plugged in to their corresponding pins on the RAMPS 1.4 board. The Z motors should be plugged into the same box, one on top of the other. The black wires should also always be the furthest to the right.



1. Plug in the extruder NEMA motor to the top left set of four pins.
2. Plug in the X NEMA motor to the bottom left set of four pins.
3. Plug in the Y motor to the bottom middle set of four pins.
4. Plug the Z motors, one on top of the other, in the bottom right sets of four pins.

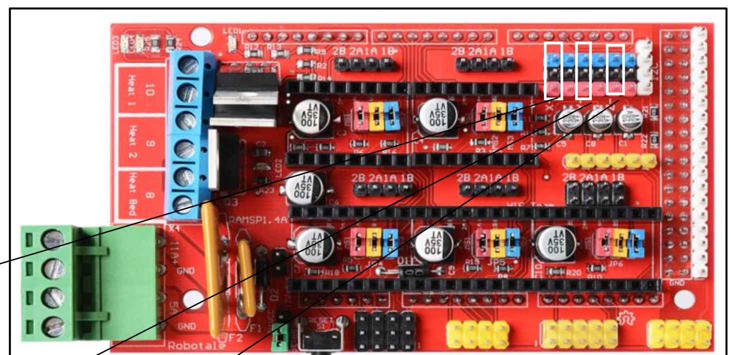
3. Plugging in the Heat Components



The heating components provide heat for the extruder to melt the filament for printing, provide a warm surface on the heatbed so the prints do not stick, and the fan prevents the extruder from overheating.

1. Plug in the extruder heater wires.
2. Plug in the extruder fan included in the E3D V6 Titan kit.
3. Plug in the heatbed wires.
4. Plug in the thermistors.

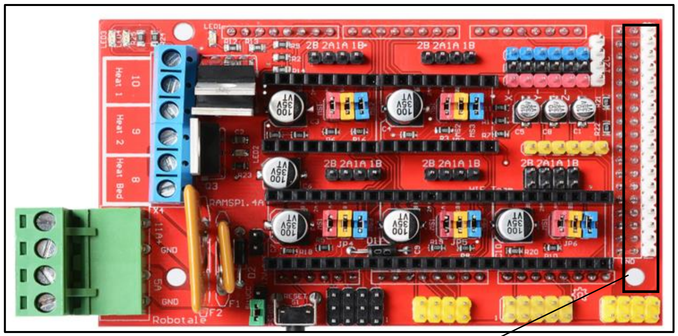
4. Plugging in the Endstops



Since only three endstops are used on this 3D printer only the X-min, Y-min, and Z minimum pins are used.

1. Connect the x direction endstop to the furthest left set of pins.
2. Connect the y direction endstop to the middle set of endstops.
3. Connect the z direction endstop to the right most set of pins.
   Note: Ensure that the endstops wires are connected in order green, black, red from top to bottom.

5. **Plugging in the LCD Screen**

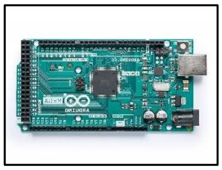


The LCD screen is used to manually control the 3D printer. It can jog the extruder and heatbed in the X, Y, Z directions as well as control the temperature of the extruder and heatbed. The LCD screen is optional since the printer itself will be operated using Pronterface software, which will be discussed further in the next chapter.

1. Connect the LCD screen to the long vertical set of pins on the far-right side of the board.

Marlin Firmware and Pronterface Download

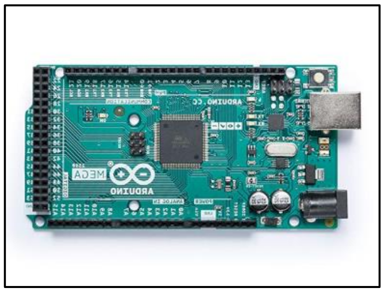
Required Parts

		
Arduino Mega 2560	USB Standard A-B Cable	Laptop or Desktop Computer with Internet Access

Marlin Firmware drives most 3D printers today, commercial and do-it-yourself. Marlin can be opened on multiple platforms, however, since this printer runs on an Arduino Mega 2560, Arduino is the platform that is used to open the Marlin code and configure the printer settings. Pronterface is a 3D printer host software, which allows the user to control their printer, without the use of an LCD screen or other manually installed controls. Pronterface allows for manual movement in the X, Y, and Z directions and can also control elements such as the temperature of the heatbed. G code can also be uploaded to Pronterface and be used to print parts easily.

Steps

1. Connecting the Arduino Board to the Computer



Once all the wiring is done, a computer can be connected to the Arduino board using the USB port and a USB A-B cord.

1. Connect the Arduino board to the computer using the USB A-B cord. The wider end should plug into the computer.

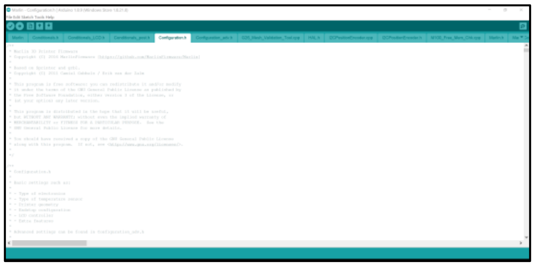
2. Downloading the Arduino App

The Arduino app allows for the Marlin code to be opened and modified based on your desired settings for the printer.

1. Download the app using this link:

   www.arduino.cc/en/Main/Software

3. Downloading the Marlin Code



Marlin in an open source firmware that controls the 3D printers, stepper drivers, heaters, sensors, extruder, and LCD display.

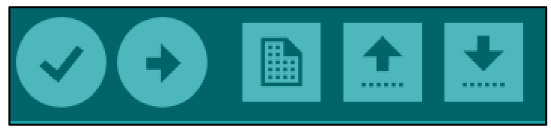
1. Download the Marlin code using this link:

   marlinfw.org/meta/download/

2. Once the file is downloaded navigate to its download location and open Marlin 1.1-x > Marlin > Marlin that should be an INO file. This will open the Marlin firmware in the Arduino platform.

4. Altering the Marlin Code

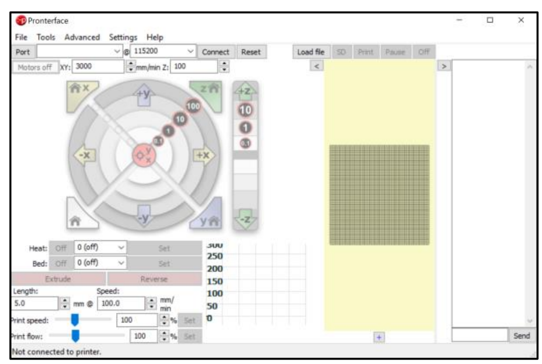
Most of the 3D printer settings can be changed in the Configuration.h tab in the arduino platform. Changes to the stepper motors, endstops, heat bed, and extruder can all be made in the Configuration.h tab. Once any changes are made, you can compile and upload the code to the Arduino board.



1. In order to compile the code and ensure that there are no errors, click the check mark located in the upper right portion of the window.
2. Once the code has compiled without any errors, click the arrow pointing to the right to upload the code to the Arduino board.

5. Pronterface

Pronterface is a free software that allows users to manually control their 3D printer from their laptops. They can jog the heatbed and extruder in the X, Y, Z directions and alter the temperature of the extruder or heatbed.



1. Use this link to download the latest version of Pronterface for either Mac or Windows:

   kliment.kapsi.fi/printrun/

2. To Upload G-code to Pronterface use the “Load File” tab in the upper right-hand corner of the Pronterface window. You are now ready to print.

3.2 Design Iteration

Multiple design iterations and changes were made to the printer throughout the design process as well as the assembly process. One issue that arose once the printer was assembled was the deformation that the rod holding brackets experienced when installed on the printer. The rods that were press fitted into the brackets, pulled the cantilevered portion of the bracket outwards and down. Since the material that the brackets were made out of was PLA, the brackets deformed relatively easily. The first design seen in Figure X1 experienced the maximum Von Mises equivalent stress at the seam where the mounting part of the bracket and the cantilevered part of the bracket meet. This was determined by executing a Finite Element Analysis using the software, ANSYS. The maximum equivalent stress of the first design when 5 N of force were applied to the bracket was 2.77 *10^6 Pa and the maximum total deformation was 1.69 *10^-6 meters.

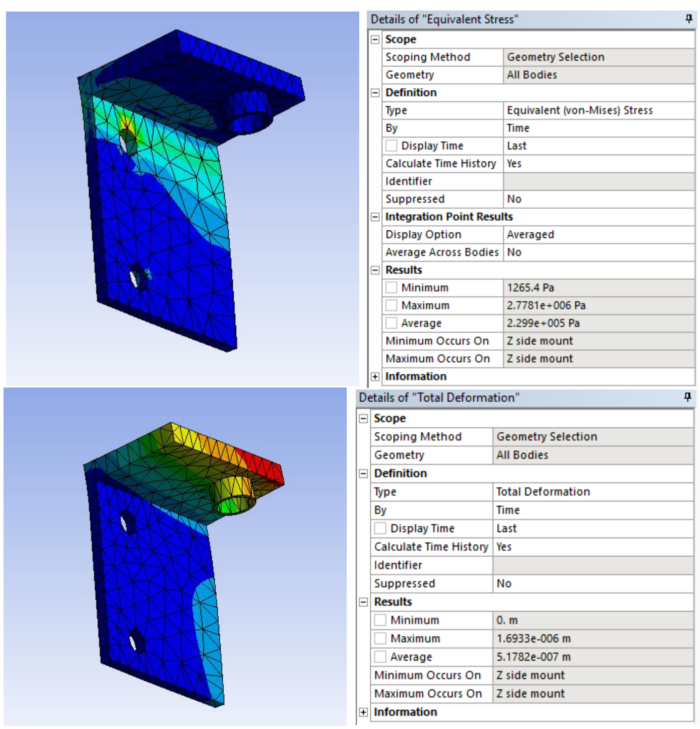
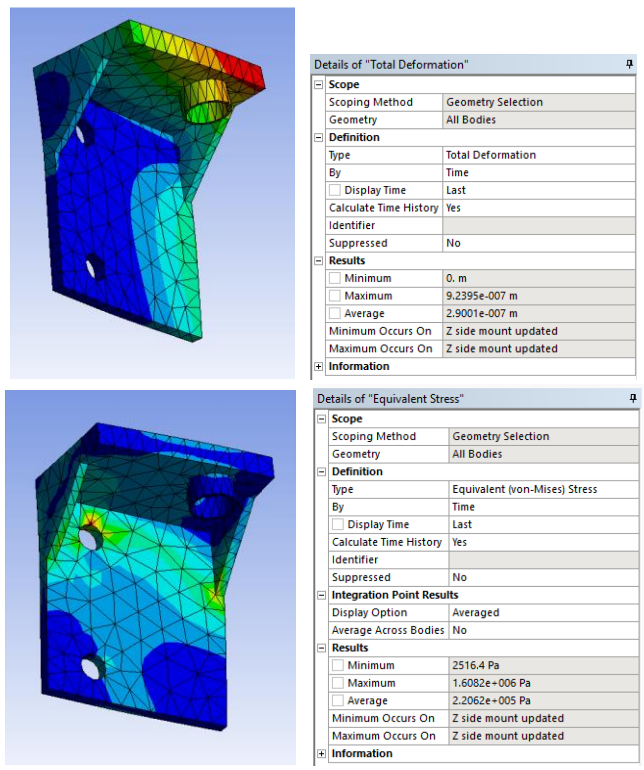


Figure 3.1: Original Bracket Equivalent Stress and Deformation

The second design iteration included gussets on the brackets in order to change the area where the maximum stress was concentrated. This bracket was also designed using SolidWorks and an FEA was completed using ANSYS to observe the new maximum equivalent stress concentration. This redesign was successful. The maximum equivalent stress concentration shifted from the seam in the part to the gusset itself. Since the gusset was sustaining the majority of the stress rather than the seam of the bracket, the part did not deform at all when installed on the 3D printer. In this case the maximum equivalent stress was decreased to 1.61*10^6 Pa and the total deformation was decreased to 9.23*10^-7 meters.



Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	0. m
Maximum	9.2395e-007 m
Average	2.9001e-007 m
Minimum Occurs On	Z side mount updated
Maximum Occurs On	Z side mount updated
Information	

Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Stress
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	2516.4 Pa
Maximum	1.6082e+006 Pa
Average	2.2062e+005 Pa
Minimum Occurs On	Z side mount updated
Maximum Occurs On	Z side mount updated
Information	

Figure 3.2: Original Bracket Equivalent Stress and Deformation

4. Filament Development

This section describes the process of how a viable PA12/NdFeB filament was produced for use in additive manufacturing. This section also includes the results of analysis performed on filaments with different weight percentages (wt%) of NdFeB.

4.1 PLA/Fe Test Filament Development Process

Prior to beginning development of a PA12/NdFeB filament, PLA polymer pellets and Fe powder were utilized in order to solidify the development process for the PA12/NdFeB filament. PLA was chosen as a test filament due to its relatively low cost and comparable material properties:

	PLA	Nylon-12 (PA12)
Density	1.29 g/cc	1.37 g/cc
Modulus of Elasticity	2.79 GPa	4.55 GPa
Additive Loading Factor	20.0%	19.6%

Table 4.1: Comparison of PLA and PA12 (Overview of Material Properties of PLA/PA12, 2019)

Fe powder was chosen as a substitute for NdFeB for similar reasons:

	Fe Powder	NdFeB Powder
Apparent Density	7.874 g/cm^3	7.5 g/cm^3
Particle Size	60 μm	50 - 60 μm

Table 4.2: Comparison of Fe and NdFeB powders (Iron Magnetic Powders, Neodymium Iron Boron Powders, 2019)

Further, clear PLA polymer pellets were used to assist in ensuring even distribution of Fe powder within the resulting filament.

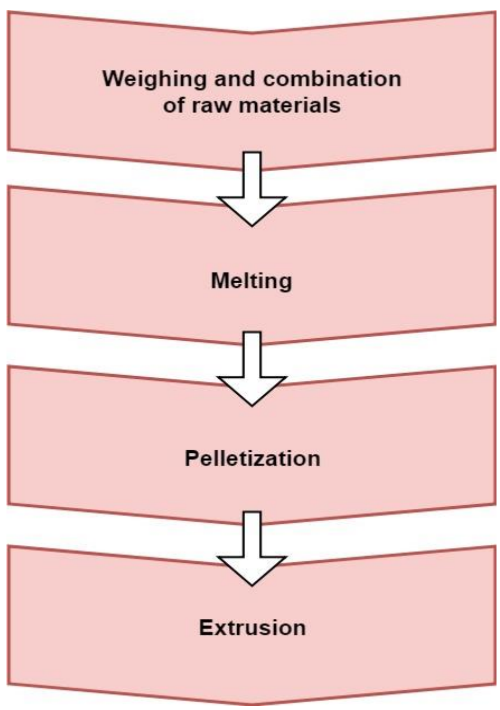


Figure 4.1: Flowchart of Filament Procedure

4.1.1 Combination of Raw Materials

Both the polymer (PLA) and additive (Fe powder) were first measured to ensure that a specific final weight percentage was obtained. For the test filament, a weight percentage of Fe of 15% was sought after. A gravity convection oven was used to heat pelletized polymer to its melting temperature. A high temperature thermometer was used to monitor the temperature of the oven to keep the polymer at a relatively consistent temperature. The polymer was placed in a crucible before being introduced to the oven until it reached approximately 180C. The polymer was rotated through the oven at 10-minute intervals and checked periodically to ensure proper melting. After the PLA sample was fully melted, it was removed from the oven and the Fe powder was added and mixed in. The PLA was then placed in the oven at 5-minute intervals, removed each time so that the material can be mixed again. After three cycles, the crucible was removed from the oven and the PLA/Fe mixture was turned out onto a wax paper sheet (approximately 5 mm thick).

4.1.2 Pelletization

Once the PLA/Fe mixture was given time to cool, it was cut into approximately 5mm x 5mm pellets using an x-acto knife. The pellets were used immediately in the extrusion step of the process.

4.1.3 Extrusion

The PLA/Fa pellets are then manually fed into a “Filastruder”, a filament extruding apparatus. The Filastruder is a single screw extruder (SSE), consisting of a motor, hopper, screw, insulated barrel, cooling fan, and melt nozzle. The barrel temperature is set via a PID controller; for the PLA mixture, the controller must be set to 180C. The barrel should be allowed 10-15 minutes to properly heat up to the set temperature. If the screw motor is engaged before the barrel is fully heated, residual material in the barrel can prevent the screw from spinning and damage the motor. After the barrel temperature stabilizes, the motor can be engaged, initiating the extruding process. PLA/Fe pellets are fed into the hopper and pulled down into the barrel by the screw, producing filament. The insulated barrel extrudes filament at a die diameter of 1.75 mm. A fan located hear the extruding end of the barrel provides convective heat transfer over the newly-extruded filament, helping to immediately lower its temperature so that the filament keeps its shape. The fan is connected to the same on/off switch as the extruder screw, and will only be on when the screw is running.

The first extrusion of the PLA/Fe mixture produced a filament that had a fairly uneven distribution of FA powder, with most of it localized to the middle few feet of extruded filament. The resulting filament was repelletized and extruded twice more to ensure even distribution of the powder. The third extrusion produced a filament that showed a consistent concentration of Fe powder throughout the PLA, along with even ferromagnetic properties along the entirety of the extrusion.

4.2 PA12/NdFeB Filament Development Process

The process for developing a viable PA12/NdFeB filament is almost identical to that of the PLA/Fe process, with a few notable exceptions. Like the PLA/Fe filament, the weight percentage of additive for the PA12/NdFeB test filament was 15%.

4.2.1 Combination of Raw Materials

The PA12 polymer used in this case did not come pre-pelletized, and was already packaged on a spool ready for use in a 3D printer. This meant that the existing PA12 filament needed to be pelletized by hand to better assist in the initial melting process. This was accomplished using an x-acto knife, with the filament cut down to 5mm pieces. Both the pelletized PA12 and NdFeB powder were weighed in order to determine the percent concentration by weight of the resulting filament.

4.2.2 Pre-dissociation of PA12

The pelletized PA12 was introduced to the oven at a temperature of 220C. After 30 minutes within the oven, the PA12 showed no signs of melting or dissociation. There were multiple theories as to why this was, including the possible presence of a protective coating on the moisture-sensitive PA12 filament, however there was nothing on the MDS to support this. The pelletized PA12 filament was instead introduced to the screw extruder, under the assumption that the combination of heat and shear forces would properly disassociate the PA12 filament.

The extruder was first purged to ensure removal of any leftover PLA polymer or Fe powder from the previous test extrusions. Pelletized PA12 was fed into the extruder hopper, and a resulting filament of pure PA12 was extruded. This resulting extrusion was pelletized to 5mm pieces using the previous x-acto knife method. The resulting quantity of PA12 was reweighed to ensure that the original intended weight concentration was consistent.

4.2.2 Melting

The extruded and pelletized PA12 was once again introduced to the oven after it had been heated to 220 C. The polymer was checked at 10-minute intervals to ensure that it properly melted. The pre-dissociated PA12 showed signs of melting after approximately 20 minutes,and was fully melted after 30 minutes. The crucible was left in the oven for an additional 10-minute interval before the NdFeB powder was added. The crucible was then removed at 5-minute intervals to ensure proper mixing of the two materials. After three mixing/heating intervals, the PA12/NdFeB mixture was turned out onto a wax paper sheet and smoothed out to a thickness of 5mm.

4.2.3 Pelletization

The resulting PA12/NdFeB was given time to cool, before being pelletized with an x-acto knife into 5mm x 5mm pieces. These pellets were used immediately in the extrusion process.

4.2.4 Extrusion

Following the pelletization process of the PA12/NdFeB mixture, the pellets can be fed through the "Filastruder" in a process similar to that of the PLA/Fe mixture. For this mixture, the PID controller must be set to 215C to ensure the extruder barrel is hot enough to support the melted PA12. Like before, the extruder barrel was allowed 15 minutes to stabilize before the screw could be engaged.

The first extrusion of PA12/NdFeB filament had a fairly consistent diameter, however it was evident that pockets of NdFeB powder were still located unevenly throughout the PA12 filament. This was determined from the numerous air pockets and the grainy and brittle texture of several sections of filament, while other sections showed the same level of ductility as the plain PA12. The resulting filament was collected and repelletized before being extruded twice more. This third extrusion produced a filament that had an even diameter and evidently even distribution of NdFeB powder. The filament showed ductility comparable to the original PA12 filament, with even ferromagnetic properties along the entirety of the filament.

Figure 4.2: i: PA12 pellets pre-dissociation, ii: NdFeB powder iii: NdFeB/PA12 mixture, iv: pelletized NdFeB/PA12, v: NdFeB/PA12 being extruded, vi: final NdFeB/PA12 filament

4.2.5 Weight Percentage Differentials

Following the initial successful extrusion of a homogenous PA12/NdFeB filament, the team investigated the possibility of using other weight percentage of NdFeB powder. The theory was that a higher weight percentage of NdFeB powder would yield a greater magnetic field once the filament was printed and magnetized, however it could sacrifice filament ductility and print quality. PA12/NdFeB filament was produced at weight percentages of 10%, 20%, 30%, 40%, and 50% NdFeB. The team worked backwards from the highest weight percentage down to the lowest.

The 50 wt% NdFeB mixture produced a brittle, uneven filament. Even after 3 trips through the filastruder, the material was not capable of holding its shape once leaving the extruder barrel, and had numerous pockets of NdFeB powder deposited along the length of the extruded mixture. Both the 40 wt% and 30 wt% showed an improvement in ductility, however neither filament was capable of producing an extrusion longer than a few inches before experiencing breaks.

Both 20 wt% and 10 wt% extruded with a consistent diameter and an even distribution of NdFeB powder. The 20 wt% filament showed greater ferromagnetic properties than both the 10 wt% filament and the 15 wt% test filament while having a comparable level of ductility. Due to these qualities, a 20 wt% NdFeB filament was pursued as the primary test filament for 3D printing.

5.0. Magnetic Alignment of Neodymium Particles through Solenoid

5.1 Magnetic Anisotropy

Magnetic anisotropy refers to an intrinsic property of a ferromagnetic material, independent of grain size and shape, that relates the crystallic orientation of the material and the applied magnetic moment required to align its crystals along the same direction (Magnetic Anisotropy, n.d.). Ferri/Ferro-magnetic materials are those possessing magnetic moments in absences of external magnetic fields, allowing a potential for significant permanent magnetization (Anderson, 2010). Within an applied magnetic field, the particle's adjacent sub-volumes align with one another in regions known as magnetic domains. Each domain has its individual preference of direction, known as the "easy direction," causing a net vector sum of zero across the entire particle/material without an external magnetic field. The relationship between the crystallic orientation of the ferromagnetic material and magnetic moment to orient domains along certain directions is pictured below (Magnetic Anisotropy, n.d.). The "easy direction" requires less of a moment to orient compared to the "hard-direction" under the same magnetic field, H [milli-Teslas] (Magnetic Anisotropy, n.d.). This relationship is a subsection of magnetic anisotropy, called magnetocrystalline anisotropy, but is a significant factor in a ferromagnets capability.

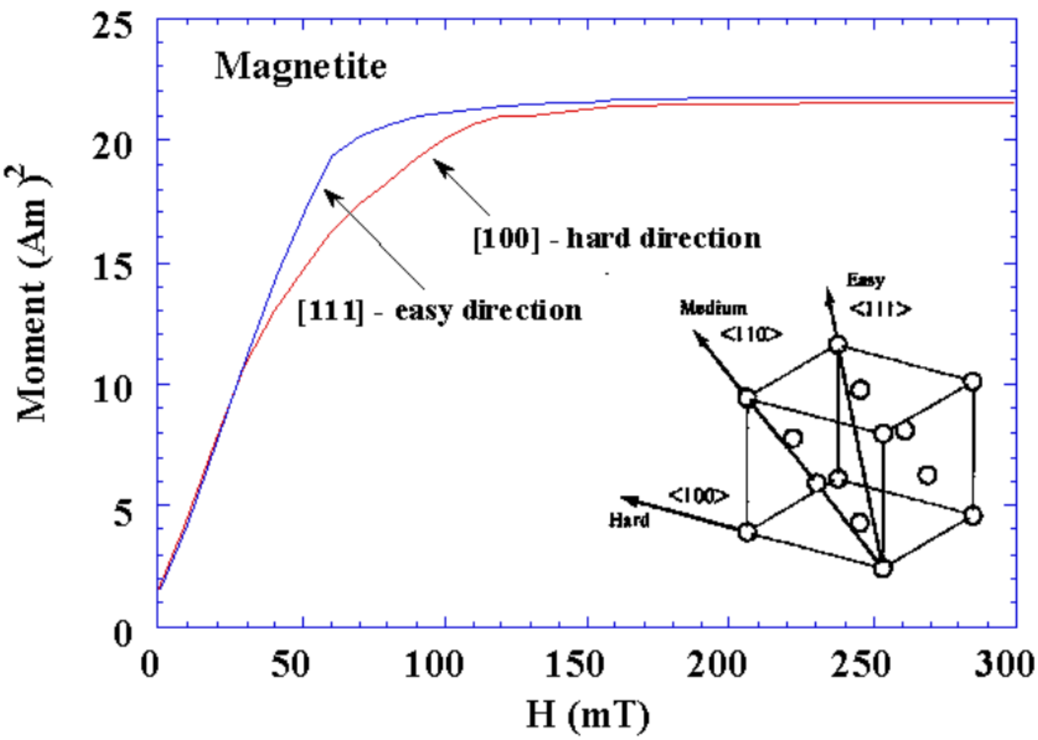


Figure 5.1: Example of Easy, Medium, and Hard Direction in a Crystalline Structure

Ferromagnetic materials' magnetic domains typically favor these "easy-directions," since magnetization in this direction is the strongest. Saturation, or the state of a materials magnetic potential being reached, is the easiest to achieve in the "easy-direction."

Ferromagnetic materials are further defined by the amount of "easy directions" that are associated with their crystalline structure. Particles can be uniaxial (one easy-direction), triaxial (easy, intermediate, and hard directions), or cubic (having three or four easy directions). In particular, neodymium has a tetragonal crystal structure with a high uniaxial magnetocrystalline anisotropy (Neodymium Magnets, 2018). The anisotropy energy associated with a uniaxial structure is equivalent to the following relationship, in which the gamma represents α, β, or Γ direction vectors, whichever is the easy direction.

$$E = KV\left(1-\gamma^2\right) = KV\sin^2\theta,$$

Where: *V = Volume*
K = Anisotropy Coefficient
*Θ = Angle between the easy direction (*α, β, or Γ*) and the particle's orientation*

5.2 Neodymium's Magnetic Properties

As previously mentioned, neodymium possesses a tetragonal crystal structure with uniaxial properties, in which its magnetic field strength relative to the magnetic moment (A*m^2) can be as high as 7 Teslas. Because of its extremely high magnetocrystalline anisotropy, the neodymium is hard to demagnetize once it has been saturated. This resistance is known as coercivity. The intense magnetic potential of this compound, and associative coercivity, is caused by the neodymium atom possessing 4 unpaired electrons. Unpaired electrons spin in the same direction to generate a magnetic field. Similar ferromagnetic materials, such as iron, only have three unpaired electrons, in which the magnetic potential is not as high as neodymium's. The saturation energy, which is the amount of magnet strength that can be achieved, for neodymium is 1.6 Teslas (16 kg), with a remnant magnetization of approximately 1.3 Teslas. Proportional to this value is maximum energy density, BHmax, which is equivalent to the saturation energy (Js) → 2*Js^2. Thus, neodymium can achieve an energy density of upwards of 512 kJ/m^3, or 64 MG*Oe as referenced previously in the report. These strength attributes of neodymium magnets are 18 times greater than a ferrite magnet by volume percentage and 12 percent larger by weight percentage. Below are other neodymium magnetic properties, which are specific to the bonded form of the compound used for this project (Neodymium Magnets, 2018):

Br, Remanence - strength of magnetic field → 0.6 - 0.7 [Tesla]

Hci, Coercivity - Resistance to de-magnetization → 600 - 1200 [kA/m]

BHmax, Magnetic energy density → 60 - 100 [kJ/m^3]

Tc, Curie Temperature → 300-400 [Celcius]

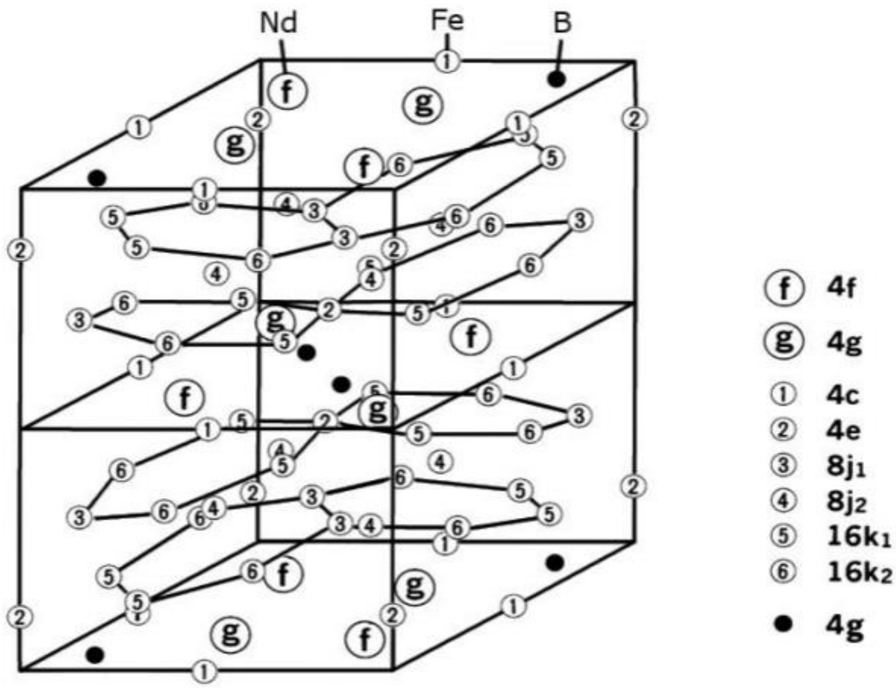


Figure 5.2 - Tetragonal Crystalline Structure of Neodymium

Another aspect to consider when implementing a magnetic field to direct orientation of the neodymium's dipoles is the rotational relaxation time the of the particle. What this introduces is when there is an applied magnetic field to the particle and it is dynamic or subject to period variation (in this case the flow of an extruded filament), it is possible that the application period is shorter than the relaxation period of the particles. This can result in the particles not directly aligning with the direction of the magnetic field (Zhang, Budnick, and Hines, 1998). As a result, the magnetized neodymiums particles will not possess their maximum saturation magnetization and yield an overall weaker magnet. Thus, it is important to maximize the length of the solenoid coil and/or speed of extrusions in order to fully saturate the neodymium particles.

5.3 Solenoid-Developed Magnetic Field

Due to its convenience, ability to be applied to the extruder nozzle, and cost effectiveness, a solenoid was chosen to produce the magnetic field applied to the neodymium PA-12 filament. A solenoid is essentially a coiled electromagnet composed of a copper wire with a specific current running through it. The magnetic field runs the same axial direction as the current runs through the coiled-wire, in which the generated uniform field is most concentrated at the center, as pictured by the diagram below (Nave, n.d.). The equation relating the generated magnetic field to the coil's parameters is $B = \mu n I$, where:

B = Magnetic Field Strength [Tesla]
μ = permeability → $\mu_0 * k = 4\Pi \times 10^{-7}$ and k is relative permeability of the coil material
n = N/L → "Turn density" or number of coil turns per unit length [turns/meter]
I = Current [A]

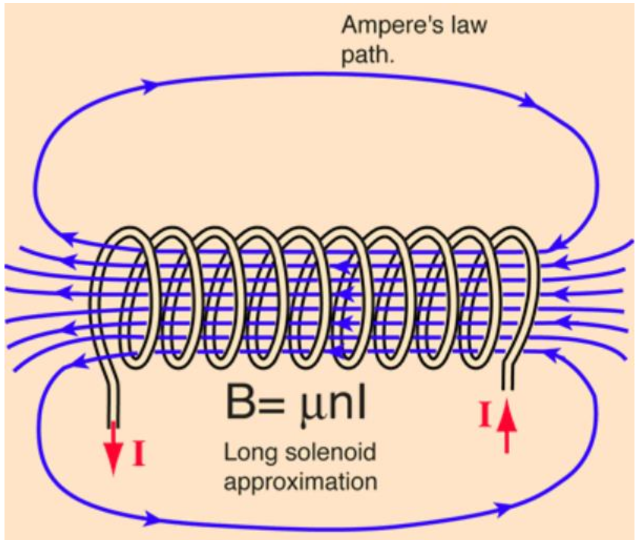


Figure 5.3: Ampere's Law Path

5.4 Production of Copper Solenoid

When creating the copper wire solenoid intended to align the filament's neodymium particles, some of the limiting factors experienced were: the length of the 3D Printer's nozzle, the wire gauge's effective resistance, the width of the coil that could be created, and the radial distance from the center of the nozzle orifice. The extruder nozzle possessed a height of 4mm and a diameter of 8 mm that the solenoid had to correspond with. The length of the coil was less than that of the coils width, in order to maintain clearanceabove the nozzle oriffice and avoid contact with pre-deposited neodymium filament (*See Figure Below)*. Additionally, 22-gauge copper wire was selected since it was thin enough to tightly wrap around the nozzle, but thick enough as to not limit the passing current. The thickness also provides some stability to the coil without a significant amount of setting-epoxy.

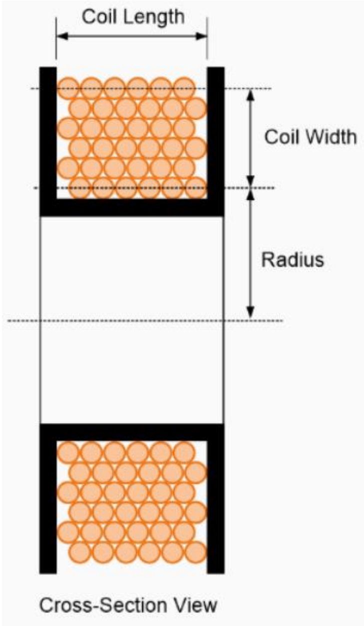


Figure 5.4: Coil Diagram

The solenoid was developed by wrapping the copper wire layered in one direction. It was imperative to maintain a consistent direction when wrapping so that the field directed the particles poles consistently. The hexagonal-shaped extruder nozzle was measured to be between 7.8 mm to 7.9 mm, the shorter from flat-face to flat-face and the latter from corner to corner. Because of this geometry, the larger of the measurements would have to be design around so that the circular solenoid could fit around the nozzle base.

Figure 5.5: Heat block and Nozzle

To wrap the solenoid tightly at a close-fitting diameter, one of the ends of the 8-mm smooth rods was used. The rod was rotated in a lathe-like fashion and the copper wire, tightly bound around the smooth rod, was wrapped between two thimbles that were 3D printed to maintain the 4-mm coil length (see below). Once a layer was finished, the copper wire was brought back to the top of the coil to begin a second layer following the same direction as the first. On alternating layers, a temperature-resistant Loctite EA 1C Epoxy Adhesive was minimally applied to cure the solenoid layers in position, without adding too much material in between to significantly separate the layers from the nozzle orifice (*note the white substance*). A very thin plastic film was inserted between the smooth rod and the first layer of the solenoid so that the solenoid could be slid off without compromising the turns of the first layer. The final product of the solenoid is pictured following the image of the solenoid wrapping arrangement.

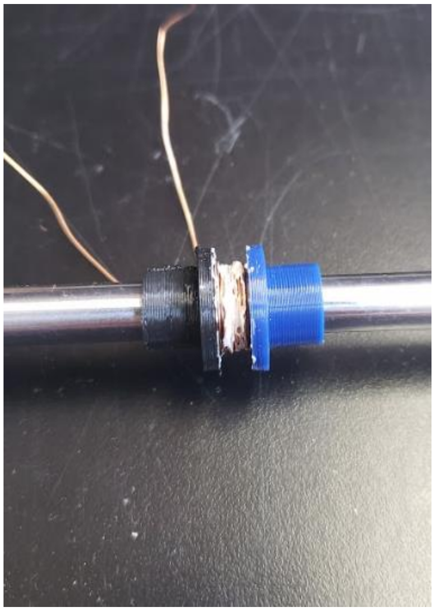


Figure 5.6: Solenoid Development

Figure 5.7: Solenoid Final Product

5.5 Magnetic Field Induced by the Solenoid

Despite the physical limitations, the solenoid was created using 50 turns, in which the 22-gauge copper wire (approximately 0.7mm in width) fit approximately 10 turns in the 4 mm length per layer, thus requiring 5 layers. From Accel Instruments' online calculator, the value of VDC required to produce the magnetic force based on the previous parameters is provided, which will help determine the method of providing current to the solenoid. In order to use this approximation, the amount of current in Amps that is expected to pass through the solenoid needs to be assumed. Since the nozzle is already expected to be hot and heat is not a limiting factor for this situation, the heat created by passing higher amounts of current through the wire was not a concern. Thus, 5A was chosen as a reasonable value, and this was used as the assumed current. Based on these parameters, the resulting magnetic field was approximately 25 mT (Accel Instruments 2019):

Coil Input Parameters

Coil Inner Radius (mm): 4 Note 1
Coil Lenghth (mm): 5 Note 2
Copper Wire Diameter with Insulation(mm): 0.7 Table 1
Copper Wire Diameter without Insulation:(mm): 0.7 Table 2
Number of Turns: 50 Note 3
Coil Current (A): 5 Note 4
Frequency (kHz): 1 Note 5
Distance from center (mm): 0 Note 6
Core Relative Permeability, k: 1 Note 7
Winding Compac-Factor: 0.9 Note 8

Figure 5.8: Coil Input Parameters

Basic Calculated Output Parameters

Magnetic Field (mT): 25.3042 Note 9
Coil Height(mm): 4.410 Note 10
DC Resistance (Ohm): 0.081 Note 11
Inductance (uH): 23.998 Note 12
Total Impedance (Ohm): 0.172 Note 13

Advanced Calculated Output Parameters

Minimum DC Driver Voltge Requried (V): 0.404 Note 14
Resonance Capacitor Capacitance (nF): 1055521.07418 Note 15
Resonance Capacitor Voltage Rating (kV): 0.001 Note 16
DC Power Dissipation (W): 2.02 Note 17
AC Power Dissipation (W): 1.02 Note 18

Figure 5.9: Coil Output Parameters

While an input voltage of 0.404V is easily achievable, the ability of the copper wire to pass higher current was the most significant factor limiting the voltage from being increased. Either through practice of increasing the voltage, increasing the wire's diameter (lowering the gauge value), or decreasing the wire's resistance, the solenoid's ability to produce a higher magnetic field shall still needs to be investigated further.

Using a Finite Element Method Magnetics software (FEMM) the magnetic field density, with the determined parameters above, can be illustrated in which the highest magnetic field density achieved is 29.6 mT, as pictured in the axisymmetric view of the solenoid. While the field drops to nearly 0 mT just millimeters out of the center of the solenoid, the filament being extruded is only 1.75 mm thick, so the maximum field density should be applied to the majority of the filament (the blue box in the illustration has sides 1 mm long for comparison).

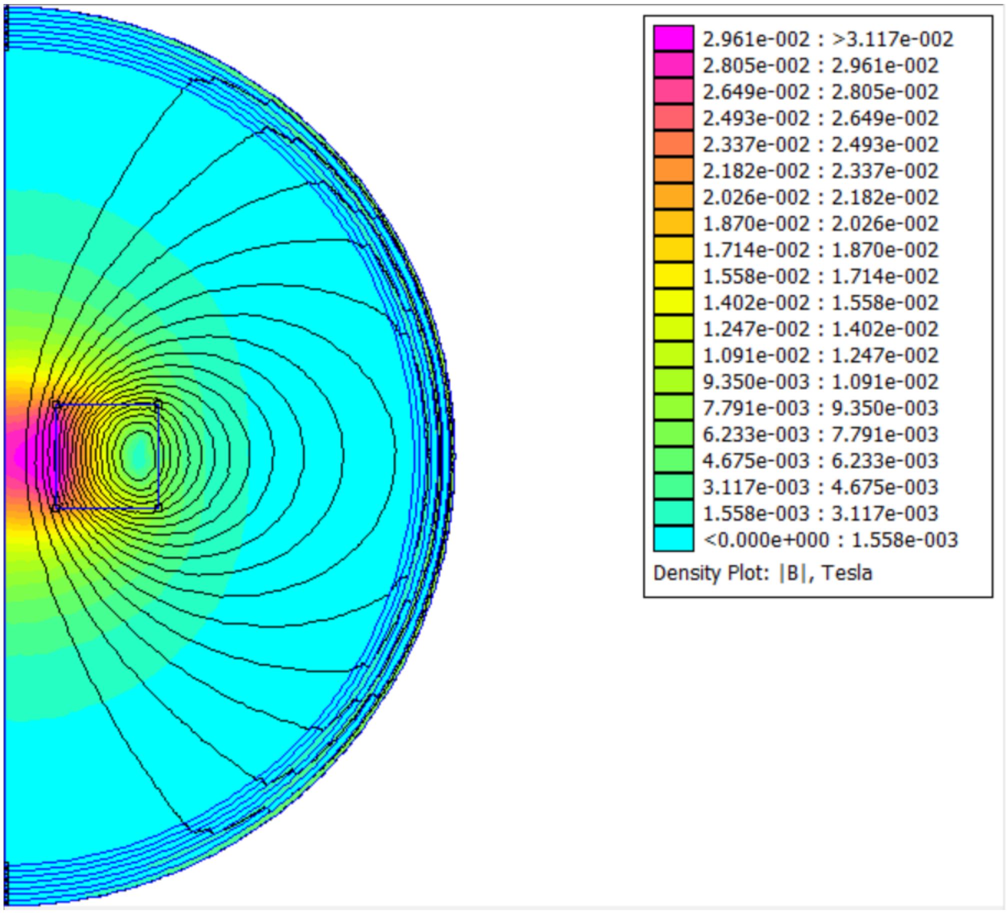


Figure 5.10: FEMM of Copper Solenoid

6. Conclusions and Recommendations

6.1 Conclusions

This preliminary project illustrated the potential for 3D printing of magnetic components. A custom 3D printer was designed and built with the intent of being modified for use with printing filaments that have magnetic properties. Ultimately, this printer was capable of printing with stock PLA filament. A custom filament comprised of NdFeB powder and PA12 was developed at different weight percentages, with a ratio of 20:80 ultimately being chosen for its favorable ductility and ferromagnetic properties. Unfortunately, while both the stock PA12 filament and the custom PA12/NdFeB filament were able to be extruded from the custom 3D printer nozzle, they were not able to be printed with the custom 3D printer.

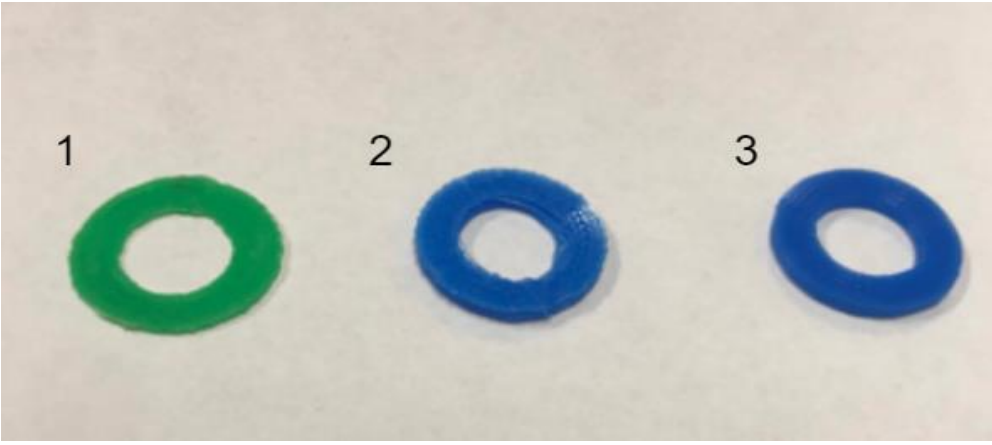


Figure 6.1: Three PLA prints from the custom 3D printer. Print 1 was the first successful cohesive print. Print 2 was performed after various calibration improvements, and print 3 was performed with the current printer setup.

6.2 Recommendations

Based on the above results, the following recommendations have been made to assist in future work on 3D printing applications of NdFeB/Pa12 filaments. These recommendations are made based primarily on the magnetic properties achieved via printing and the overall print quality of the custom 3D printer.

6.2.1 Printer Improvements

Currently, the custom 3D printer has difficulty consistently printing with both the PA12 stock filament and the custom PA12/NdFeB filament. This is assumed to be a result of the relatively high temperatures at which PA12 must be printed. An immediate improvement to the printer would be to upgrade the current hot end to one capable of printing at temperatures above 250°C. This may also require modification of the current Marlin code, and possibly the use of a board that is more powerful than the RAMPS 1.4. Further, the current printer bed may need to be upgraded in order to promote better print adhesion, and an enclosure for the printer may need to be developed so that the hydroscopic PA12 filament faces less exposure to the atmosphere during printing.

6.2.2 Solenoid

The procedure for developing a viable printer-mounted solenoid must be improved in order to meet the criteria established in Section 5. The current winding procedure is only capable of producing a solenoid with 20 turns at most, far below the 50 turns recommended to align the NdFeB particles during printing. The solenoid is limited in width due to the relatively small length of the nozzle, meaning that the extra turns must be added in additional layers. These additional layers require the use of more epoxy, making the solenoid heavier and more likely to come undone. While weight is an issue, it is not recommended that a smaller wire gauge is used, as this will result in the need for more turns and therefore more layers.

6.2.3 Post-print Magnetization

While there are various hurdles that must be overcome before this step, research must still be conducted into the feasibility of magnetizing any 3D printed parts. As stated above, any 3D printed parts will lose their ability to produce a magnetic field on their own after being run through the extruder due to the Curie effect. While the printer-mounted solenoid will theoretically realign the magnetic particles within the filament, the parts will still need to be exposed to a strong magnetic field in order to remagnetize them. Preliminary research suggests that this field must be in the order of 2.5 Teslas in order to effectively induce magnetization with the NdFeB powder.

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An Examination of the Technical Writing Genre Through a 3D Printer Manual Case Study

A Major Qualifying Project
submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
Degree of Bachelor of Science

Submitted By:
Miles Nallen, Professional Writing and Mechanical Engineering

Advised By:
Kevin Lewis, Professional Writing

This report represents the work of one of more WPI undergraduate students submitted to the faculty as evidence of completion of degree requirements. WPI routinely publishes these reports on its web site without editorial or peer review

CONTENTS

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Abstract

The purpose of this project was to create a manual that explains, step-by-step, how to build a 3D printer and examine the best practices of technical manual writing. The manual was written based on technical writing best practices determined through literature review. This manual was then provided to focus groups to obtain feedback on the manual itself and how well it represents the technical writing genre and any inconsistencies with technical writing best practices.

1. Introduction

Instructional manuals from the likes of Virtruvius' *The Ten Books on Architecture* to James Watt's *Directions for Using the Patent Portable Copying Machines* have been around for thousands of years and have aided multitudes of people in important day to day tasks that they otherwise would not have been able to complete (Svenvold, 2015). Instructional manuals serve a very important purpose as a step-by-step guide for various projects; however, they can also reveal important information about the time and place they were written in (Schumacher, 2018). They can serve very different purposes ranging from corporate to technical documentation, or basic how-to instructional guides. Most technology today is designed with simplicity in mind and although user manuals for an iPhone, for example, may only be a page long, there will always be a need for manuals for the sake of building or troubleshooting products.

Aside from Virtruvius' *The Ten Books On Architecture* there are very few instructional manuals that detail a process from the state of collecting raw materials to a fully constructed object. With the rise in the availability of open source technology, it is now possible to download code, software, or even entire 3D designs for free. There is an abundance of open source software available, however, according to the Free Software Foundation "The biggest deficiency in free operating systems is not in the software – it is the lack of good free manuals we can include in these systems" (Seravo, 2013). This problem is especially true for the 3D printing industry.

After the patents on fused filament expired in the early 2000's a company called RepRap (self-replicating rapid prototyper) achieved the goal of releasing an open license 3D printer that could print parts for itself (Pearce, 2017). Since then, hundreds of companies, hobbyists, and large-scale 3D printer manufacturers, such as Ultimaker, have built upon RepRap's open source software and technology. As a result, it is possible to build a 3D printer from scratch with a combination of 3D printer parts from free-to-download designs on the internet and hardware from Amazon or other large online retailers. This allows many individuals and companies to affordably construct their own 3D printers. However, similar to open source software, there is simply a lack of manuals on how to assemble a 3D printer from scratch once all of these components have been gathered.

In order to fulfill our Mechanical Engineering degree requirement, my team and I built a 3D printer from scratch and modified it to print magnetic filament. The issue we ran into as we built this printer was that there were very few resources on how to actually build a 3D printer. We found one or two YouTube videos with links in the descriptions of where to buy the parts used in the video, but usually the videos were very unclear and hard to follow. We also tried using elements from the Prusa MK3 printer but found that those manuals were really only useful for assembling a Prusa kit. The Prusa manual never explained the purpose or details behind the assembly steps – it was mainly just pictures and arrows to indicate the order of assembly. As a result, it was clear that a detailed manual outlining the process of how to build your own 3D printer from the purchasing of parts, through assembly would be useful to future students or hobbyists.

This report aims to provide background research and methods on how to write a step-by-step document detailing the process of building a 3D printer from scratch. Based on the research and methods discussed in this report, I wrote a manual for the 3D printer that I built for my mechanical engineering MQP. Once the manual was finished, I conducted focus groups in order to receive feedback on the manual. From there, I used the analyzed the feedback in relation to the technical writing best practices I had determined in the background research. In order to create a manual for a complex multi-step building process it was first necessary to look at other 3D printer manuals and technical writing best practices recommended by reputable sources such as Mircosoft and the *Handbook of Technical Writing*. The inherent value in do-it-yourself projects is the flexibility that comes along with it. Although it is impossible to address every avenue or path that an engineer, hobbyist, or company might take in building their own 3D printer, this manual will show one method of building a 3D printer in detail. The following chapter covers the following:

- Research on the purpose of a manual.
- Different types and uses of a manual.
- How to outline a manual.
- How to appropriately use figures.
- Elements of technical writing such as word choice and sentence structure.
- Preexisting 3D printer manuals.

The third chapter describes the methods used in writing the manual, as well as delivering it to users and the decision-making behind these processes. The last chapter includes feedback on the manual from focus groups, a review of the manual itself, the manual creation process, and what could have been improved upon.

1.1 Applying Background Research to the 3D Printer Manual

At the end of every section in the background chapter there is a subsection that explains how the concepts discussed in the chapter were applied when I wrote the 3D printer manual. Certain concepts proved to be more useful than others, but various elements of all concepts were applied when writing the manual even if the concepts themselves were not directly pertinent. The font used for these subsections is also blue in order to indicate to the reader that the subsection will discuss decisions made directly related to writing the 3D printer manual.

2. Background

Different types of instructional manuals are created for a wide variety of uses, whether it be streamlining business processes, providing instruction on how to use a technical software, or simply putting together a piece of Ikea furniture. Frustrating and unclear manuals are unfortunately common and that is why it is important to understand the various elements of technical writing and communication that are required to write a truly useful instructional manual. Some of the most important elements to consider when writing a manual are the purpose, what type of manual is necessary for the topic, utilizing proper technical writing methodologies, how to collect and analyze feedback, and comparisons with other successful industry manuals.

2.1 The Purpose of a Manual

The need for a manual arises from complex multi-step processes that will be performed many times by many different people. The process or processes determines the subject matter of the manual, but the purpose of the manual is dictated by the audience, the scope, and the necessity for clear and concise instructions regardless of the methods of delivery. Before an outline or rough draft of a manual can even be written, it is crucial to identify the audience and their needs. From there it is necessary to define the scope of the document and decide the higher-level method of providing instructions for the user and how they should logically work through the manual.

2.1.1 TARGET AUDIENCE

Before composing a document and making content-based decisions it is crucial to first ask high level questions about the audience. The *Microsoft Manual of Style* recommends questions such as (Microsoft Press, 2014):

- Who is the intended audience?
- What is the user trying to accomplish?
- What type of content will best meet your users' needs and your objectives?
- How will the user access the documents?

Kyle Wiens, CEO of iFixit, says that knowing the target audience allows for the writers to adjust their style to the appropriate reading level (Wiens & Bluff, 2018). For example, iFixit's repair manual for Apple's Macbook Pro scored at a fourth-grade reading level on the Flesh-Kincaid scale, while Apple's own manual for the Macbook Pro scored at a reading grade level of 24. A reading level of 24 does not exist, so this just goes to show that Apple's Macbook Pro was literally off the charts and very difficult to understand for the average user. For reference, Shakespeare's Macbeth was scored at an 11^{th} grade reading level. The lower the reading and simplicity level the more accessible and easier to use a manual will be, which is one of the most important factors in writing a successful manual. Certain tools to measure reading levels include the Flesch-Kincaid Scale, websites like the Readability Test Tool, and Word and Excel, which have built in readability tools.

2.1.2 DEFINING THE SCOPE

Scope is the depth and breadth of detail covered by a document based on the audience's needs (Alred, Brusaw, & Oliu, 2009). Once the target audience is identified, the scope of the project can be determined. This is an important part of the planning process because, otherwise, time will be wasted on unnecessary research that is not even necessary to the basic function of the manual. In the *Handbook of Technical Writing* the authors provide the example of a report on facility locations. In the report it would be necessary to provide information such as "land and building costs, available labor force, cultural issues, transportation options, and proximity to suppliers" (Alred, Brusaw, & Oliu, 2009). However, a detailed history on the cities being considered for the facilities would be excessive and a waste of the writer and user's time. The scope for manuals is also somewhat inherently limiting since it is difficult to effectively cover more than one product or process in one manual without it becoming confusing or overly cumbersome for the user.

In order to achieve a realistic and manageable scope it is important to begin with a scope statement that should consist of a clear set of goals. If this is not done, "scope creep" can occur and potentially delay or even derail the project altogether (Larson & Larson, 2009). Scope creep is when additional features and details continue to be added on to the document. Scope creep can cause project deadlines to be missed, reduce the quality of integral components of the document, and lead to a confusing manual with no clear direction or purpose. Some level of scope creep is inevitable and acceptable if it falls within the original goals set for the scope of the project during the planning process.

2.1.3 HOW TO PROVIDE INSTRUCTION

The basic function of a manual is to provide instructions on a process. Those instructions can be presented in a multitude of ways, however, in the end they need to be able to communicate a clear message. One model that has been commonly used in all forms of teaching, training, or instruction since its creation in 1956 is Benjamin Bloom's *Taxonomy of Educational Objectives*. According to Mary Forehand, Bloom's taxonomy is a multi-tiered model of classifying thinking according to six levels of cognitive complexity (Forehand, 2005). The levels are often depicted as a staircase or pyramid and students or learners are encouraged to start at the lowest level which is knowledge, and work their way up to comprehension, application, analysis, synthesis, and evaluation (Forehand, 2005). In 2001, one of Bloom's former students Lorin Anderson, along with a team of cognitive psychologists, curriculum theorists, and instructional researchers, updated the taxonomy to be applicable to a broader audience. As a result, significantly more emphasis was placed upon curriculum planning and instructional delivery. The number of levels in the taxonomy remained the same but the terminology changed. In the updated version, the lowest level of thought was remembering and from there evolved into understanding, applying, analyzing, and evaluating, and creating. These new levels were defined as the following by Anderson and Krathwhohl (2001):

> **Remembering:** Retrieving, recognizing, and recalling relevant knowledge from long-term memory.
>
> **Understanding:** Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.
>
> **Applying:** Carrying out or using a procedure for executing or implementing.
>
> **Analyzing:** Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.
>
> **Evaluating:** Making judgments based on criteria and standards through checking and critiquing.

Creating: Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing. (p. 67-68).

These six levels can aid technical manual writers because, ultimately, this is the thought process they want the user to go through as they read the manual and work towards the end product. For instance, it is important to remind the user of the function of certain tools and components. In order to give further context and help the user understand a step in a manual, adequate explanation is required whether it be through text, video, or graphics. From there the user should be able to apply what they have read and physically carry out the instruction. Reminders can also be provided to help the user analyze and evaluate the current state of their project to ensure nothing has been assembled incorrectly or will need to be taken apart. Ideally, the user will then be capable of recreating that step on their own, if necessary. This requires lesser instruction the second time leading to a less cluttered manual. Bloom's Taxonomy was not specifically created for technical writing, however, utilizing the cognitive process of lower order to higher order thinking can improve the overall quality of any manual.

From a lower-order perspective, some of the most important factors in designing useful instructions result from considering the manual from the users' perspective. For instance, in his book *Technical Communication* Mike Markel says that it is important to consider the following (Markel and Selber, 2012, 590):

- Who should carry out this task?
- Why should the reader carry out this task?
- When should the reader carry out this task?
- What safety measures or concerns should the user be aware of?
- What items will the reader need?

The author can determine the answers to many of the questions when they are determining the audience for their manual, as discussed earlier in the chapter. However, without considering these questions at all, no matter how detailed the instructions provided are, they will be confusing because they do not consider the user's perspective.

From a logistical standpoint Markel also provides a few basic rules to follow to ensure instructions are clear and concise (Markel and Selber, 2012, 591).

- **Do not provide too much information in each instruction**: Too much information in one step can intimidate and confuse the reader when trying to understand what is supposed to be accomplished.
- **Use the imperative mood**: Using the imperative mood means providing direct instructions such as "Attach the red wire" rather than "You should attach the red wire" or "The operator should attach the red wire".
- **Include appropriate graphics**: Provide the appropriate amount and type of graphics for an instruction.
- **Do not omit articles to save space**: Omitting "a, an, and the" to try and save space will just make the instructions more difficult to understand and unprofessional.

Although these rules might seem basic it is important to keep them in mind when drafting instructions otherwise, just as if the users' perspective is not considered, the instructions will be unclear and difficult to follow.

2.1.4 THE PURPOSE OF THE 3D PRINTER MANUAL

For the 3D printer manual, the intended audience is users with an engineering background. This is because the use of SolidWorks, a design software, and 3D printing is necessary for some of the parts required to build the printer. The goal of the manual created for this MQP is for users to be able to assemble a fully functional 3D printer. Based on the intended audience and the goal of this manual, most of the content and instructions cater to visual learners, since many engineers are visual learners or are trained to think visually.

In order to maintain a realistic scope and prevent scope creep in this project, I created a timeline and set of goals for this project at its start in A term. A deadline for each chapter was set for every few weeks and major milestones such as drafts of the final report and manual were set for the end of B term and C term. This also allowed for multiple drafts of the report and manual to be written in addition to avoiding scope creep and an overloaded project.

The principles of Bloom's Taxonomy were not followed to the letter in the manual, however, each step in the manual was broken down into the structure of context and subsections. Before each step and sub-step there would be a few sentences of context for the user to explain the significance of the step in the overall assembly or connect it to the previous step. This allowed the user to remember, understand, and apply what they had already learned in previous steps. In a manual, the user should not have to analyze the instructions, or assembly of the product. Although it is important for the user to have the critical thinking skills to determine if they completed a task wrong, forcing the user to analyze or evaluate each step would be confusing and cumbersome.

The instructions for the manual were written based on Markel's guidelines for providing instructions. The context paragraphs at the opening of each chapter and the context provided before each sub-step was an attempt to explain why the user should carry out a task and the required parts and tools sectioned clearly detailed the items a user would need for each chapter. Imperative mood was also used consistently in each step and figures were also included for every sub-step and required parts and tools sections.

2.2 Types of Manuals

Different manuals serve different purposes and cater to different audiences. Some types of manuals detail processes for equipment setup, operation, and maintenance for beginners. This section will provide insight into different types of manuals including user manuals, tutorials, training manuals, operator's manuals, and service manuals. The manual written for this project was a user manual, but it is important to be aware of the elements of different types of manuals so they can be implemented, if applicable.

2.2.1 USER MANUALS

User manuals are written for beginner users and strive to provide instruction from the beginning of a user's experience, the setup, all the way through operation and maintenance of the product (Alred, Brusaw, & Oliu, 2009). User manuals essentially help people with little technical experience or subject matter knowledge, to accomplish a task without expert assistance (Singh, 2017). Since they cater to beginners, user manuals should be easy to use, concise, and devoid of technical jargon. The language used should be as simple and easy to understand as possible and, structurally, the focus should be on readability. Readability means that information can be found quickly and easily without having to sort through a confusing document. While user manuals can document lengthy and complex problems their main purpose is simplicity for their beginner audience.

2.2.2 TUTORIALS

Tutorials are guides that can either accompany user manuals or stand alone as electronic aids (Alred, Brusaw, & Oliu, 2009). The purpose of tutorials is to teach by providing examples rather than written instructions for the user to follow. Tutorials can rely on text-based examples, but for technical building purposes it is more helpful to either have frequent chronologically accurate images or videos (Wisch, 2018). Nowadays, with the convenience of smart phones, high quality videos can be recorded and stored easily. As a result, they have become the preferred method of tutorials for many engineers, technicians, and hobbyists.

2.2.3 TRAINING MANUALS

Training manuals are used to teach individuals, usually in a professional setting, a procedure or skill that they will be required to repeat competently on a regular basis (Alred, Brusaw, & Oliu, 2009). Since training manuals are usually used in a professional setting where performance and repeatability is important, many training manuals focus on objectives and knowledge retention (Amidor, 2016). For example, at the beginning of many training manuals there will be learning objectives for the user to reference to ensure that once they are finished reading or using the manual they are proficient in the required tasks. Many training manuals also include a desired completion timeline and even an assessment at the end to ensure that the knowledge from the manual was retained.

2.2.4 OPERATOR’S MANUALS

Operator manuals are usually written for users that are already somewhat familiar with the process or skill that is covered in the manual (Alred, Brusaw, & Oliu, 2009). They are also delivered in a variety of forms from hard packets, to being taped to machines since they are generally used in construction, computer, or manufacturing environments. Operator’s manuals, like training manuals, also have a very specific purpose. Since they are written with advanced users in mind, they mainly serve as reminders and a method of quickly training new workers

(Kujala, 2012). Operator's manuals need to be mainly visual and simple to increase efficiency and reduce time spent reading the manual. Operator's manuals do not need to contain background information on design choices, it only requires visuals with minimal accompanying text. Safety hazards should also be included with bright warnings and symbols to serve as constant reminders for operators.

2.2.5 SERVICE MANUALS

Service manuals are written with the purpose of aiding trained technicians in repairing technical equipment (Alred, Brusaw, & Oliu, 2009). These manuals usually contain trouble shooting guides and the blue prints or drawing of the machine or product. The term "service" in this context means that something most likely broke and that the purpose of this manual is for the technician coming to the customer's location to fix it. These manuals are as detailed and technically oriented as possible so the technician, even if they are not familiar with the product, can locate and fix even the most difficult to find problems.

2.2.6 TYPE OF MANUAL USED FOR THE 3D PRINTER MANUAL

A user manual is the specific type of manual that was created for the 3D printer in this project. The language was made as simple as possible and the visuals in the manual contained large pictures visuals for each step, often with arrows or other visual aids that showed the assembly order of a step or part. The document was also structured with page numbers, consistent headings and subheadings, and a table of contents in order for the user to easily find the content that they are looking for. Although the other types of manuals mentioned in this chapter do not pertain directly to the manual created for this project, it was important to still understand the other types of manuals and any elements that could be applied from them for the sake of this project

2.3 Outlining a Manual

According to the *Handbook of Technical Writing* an outline is the skeleton of the document that is being written and should list the main topics and subtopics of the subject matter in a logical method of development (Alred, Brusaw, & Oliu, 2009). Outlining a manual or any sort of technical document is useful because it breaks large complex subjects into more manageable parts. It also serves as a road map and can prevent logical errors and allow for easier reorganization of the document later, if necessary.

2.3.1. OUTLINING ACCODING TO THE *HANDBOOK OF TECHNICAL WRITING*

The *Handbook of Technical Writing* says the following:

1. The first step in outlining large and complex topics is to group related subjects into categories (Alred, Brusaw, & Oliu, 2009).
2. Categorized topics can be sorted into major and minor heading divisions based on complexity and importance.
3. Major divisions can be signified using Roman numerals and minor divisions can be denoted using capital letters. If further sub levels are needed than Arabic numerals and lower-case letters can also be used.
4. The outline should follow a consistent parallel structure for the sake of organization and following a logical order. Sub levels should not go past the fourth level otherwise they may become too cumbersome and lose their worth for the purpose of the outline.

The proper structure can be seen below:

I. First-level Heading

  A. Second-level Heading

    1. Third-level Heading

      a. Fourth-level Heading

According to the *Handbook of Technical Writing*, the last step, once the titles of the headings and subheadings are decided upon, is to write complete sentences and from there paragraphs for each heading and sub heading (Alred, Brusaw, & Oliu, 2009). This can easily be imported into the desired word-processing software and aid in the creation of a first draft.

2.3.2. OUTLINING ACCORDING TO THE *PRISMNET*

The *PrismNet*, an online textbook written by Professor David McMurrey from the University of Texas, approaches outlining in a somewhat similar way to the *Handbook of Technical Writing*, but there are some key differences.

1. The first step in the *PrismNet* process is to generate outline elements by brainstorming (McMurrey, 2014). These elements can be a rough list of terms or concepts, related to the overall topic of the document.
2. These concepts should then be grouped for organization, similar to the approach used in the *Handbook of Technical Writing*.
3. These groups can then be sequenced in a variety of different ways. The first and perhaps the most obvious method is chronological order. Whichever step comes first in the process should come first in the outline. Another method of sequencing topics in the outline is from a mechanical at-rest to in-motion sequence.

For example:

II. Basic Components of Wind-Powered
    Electrical Systems
    A. Rotor *(motionless)*
    B. Generator
    C. Tower
III. Basic Operation of Wind-Powered
    Electrical Systems
    A. Wind energy into mechanical energy
    B. Mechanical energy into electrical *(in motion)*
      energy
    C. Stabilization of electrical energy
    D. Conversion to household current

Figure 1: At-rest to In-motion Sequence

In Figure 1 the components of electrical wind power systems are first listed in the outline and are then list listed in the next section based on their functional motion. Another method is rhetorical sequencing. Rhetorical sequencing can mean:

- Simple to complex
- Least important to most important
- Least controversial to most controversial
- Least convincing to most convincing
- Least interesting to most interesting

Rhetorical sequencing is all based on the desired impact the writer wants a subject or topic to have on the reader. After the method of sequencing is decided upon, the rough outline can be elaborated. This means creating subdivisions under the original heading and condensing or simplifying concepts into one or more subdivisions.

The main difference between the *PrismNet* method of outlining and the *Handbook of Technical Writing* method of outlining is that the *Handbook of Technical Writing* is more focused on the structure of the headings and subheadings while the *PrismNet* method is more focused brainstorming and the sequencing of content and how that can potentially impact the reader.

2.3.3 OUTLINING THE 3D PRINTER MANUAL

I used outlining methods from both the *PrismNet* method and the *Handbook of Technical Writing* to outline the 3D Printer Manual. As suggested in the *Handbook of Technical Writing*, levels and sublevels were used in the outlining process of the manual. The three sublevels were: headings, steps, and sub-steps. Instead of using Roman numerals for the outline, however, Arabic numbers and letters were used. This was because in the final draft of the manual, no roman numerals were used, so it did not make sense to use them when authoring the content in the outline and then have to change them later on.

One of the most challenging aspects of outlining the manual was determining the rhetorical sequencing, as discussed in *PrismNet*. This is because the manual was written after the 3D printer was already built, not at the same time. During the building process of the printer, there were many times when the team had to take apart the printer and back track because they had forgotten to include something or had assembled something incorrectly. It was crucial to determine the proper order of assembly of the 3D printer in order to prevent the users from also having to take the printer apart and become confused. One example of this is the cross-bar chapter of the manual. The cross-bar installation, although very simple, is one of the last chapters in the manual. The reason for this is that if the cross bar is attached then the brackets for the smooth rods can not be attached. This would force the user to have to take the cross bar off once they reached the installation of the smooth rod brackets. This example clearly shows how important rhetorical sequencing was in the outlining process.

2.4 Visuals in Technical Writing

Visuals are used in technical writing to explain abstract concepts or instructions that cannot accurately be conveyed by words alone (Markel and Selber, 2012, 319). Visuals can represent quantities, processes or hierarchical relationships. This can include the following:

- Graphs
- Tables
- Drawings
- Photographs
- Maps
- Flowcharts

In addition to being able to more clearly explain concepts than the written word, visuals can provide a much more simple and concise method of communication. It is important to understand how to properly format and provide context for visuals so that they serve their intended purpose. The following subsections discuss the two main different types of visuals (tables and figures) used in technical writing and how to integrate them so that they can be effective.

2.4.1 INTERGRATING VISUALS INTO TEXT

When writing the first draft it is important to decide where visuals will best advance the purpose of the writing (Markel and Selber, 2012, 309). In the outlining process it is important to make a placeholder for the illustration that will go there or a rough sketch of a visual that might be used in a specific section. As a rule of thumb, no visual should precede where it is mentioned in the text. Visuals should also be referred to by type. For example, Figure “X” or Table “Y”. In some manuals, like software documentation for example, which has many steps, pictures or screenshots are included next to each step and are simply referred to using phrases such as “the following example shows…” rather than figure or table numbers. The amount of description will vary for each visual depending on the amount of background the intended audience is expected to have on the subject matter. Decoration, or visuals without any relationship to the subject matter, should be avoided since it will only serve to distract or confuse the reader (Stiefel, 2017). The visual should also be entirely clear and legible otherwise the intended meaning could be lost entirely.

An important aspect of integrating visuals into text is making sure that they are properly formatted. Line types, symbols, and patterns should all be clearly distinguishable and contrasting colors and lettering should be used for emphasis, rather than just black and white. If there are more than two-line types or symbols, a clearly labeled and legible key should be created to accompany the visual (Michigan State University, 2007).

White space and proximity are also important aspects of integrating visuals into a document. Without an appropriate amount of white space and even spacing between visuals, the document can appear crowded and infringe on any text that is present. This not only makes the document hard to read, but it is also unprofessional and will make users less likely to use the manual.

Whenever a landmark or road name is referenced in the text, the corresponding visual should be accurately labeled with the title of the landmark or road name. All visuals should be horizontally centered, within the margins of the report (Michigan State University, 2007). If landscape orientation is used, the base of the visual should be oriented towards the right-hand side of the page with the text or descriptions on the left-hand side. The visual should represent 1/3 of the page width and the text should represent the other 2/3. If applicable for the manual type, every visual should be labeled by its type, either figure, table, or graph, followed by its number in the order. For the title of the visual a bold font two points smaller than the text should be used and formatted consistently throughout the document.

2.4.2. FIGURES

Figures can be a variety of different visuals such as graphs, diagrams, photos, screenshots, drawings or maps. The most important factor in deciding which type of figure to use is the message that needs to be conveyed to the reader (University of North Carolina at Chapel Hill, 2018).

Illustration Type	**Purpose**
Map/Photograph	Useful for accurately portraying spatial relationships.
Pie Chart/Bar Graph	Useful for showing proportions.
Line Graph/Scatterplot	Any relationship between two variables.

Table 1: Illustration Types

It is also important to consider the method in which the manual or technical document will be read. If the document solely exists online than it is not necessary to worry about the importance of the colors in an image. However, if the document is going to be printed, the colors in the image should not affect the clarity of the image, in case users print in black and white.

Arguably, the most common type of figure used in technical writing is a quantitative figure, e.g. a graph or chart. Different types of quantitative figures include pie charts, bar graphs, scatter plots, and line graphs (University of North Carolina at Chapel Hill, 2018).

- **Pie charts:** Used for when the data being analyzed adds up conveniently to 100 percent.
- **Bar graphs:** Useful for displaying proportions, specifically, the relationship between independent and dependent variables where the independence variables are discrete (University of North Carolina at Chapel Hill, 2018).

- **Scatterplots:** The x, y coordinate system is used and each point represents a single datum (University of North Carolina at Chapel Hill, 2018). Line graphs also display data along the x and y coordinate axes. The difference between
- **Line graphs:** Depict a change in one variable as a result of another, so one is always dependent on the other. Individual points on a line graph are joined together by the line which allows for individual points as well as the overall trend of the data to be analyzed.

2.4.3 TABLES

Tables should be used if there are more than three to four data entries or when comparing larger sets of data which cannot be compared through a graph. Tables should also include a title, column titles, and of course, the data in the body of the table (Michigan State University, 2007). The title of the table should always be formatted above the table itself (University of North Carolina at Chapel Hill, 2018). The organization of tables is important. Without proper organization the data is unclear and turns into a random assortment of numbers. The title of a table almost serves as the topics sentence of the table itself and because of this should be clear, descriptive, concise, and provide a description of how the table is organized. The column titles of a table should be short, so the reader can determine the categories of the data at a glance. The unit of the data should also be included in the column title, so it does not have to be listed in ever cell and clutter the data. For the data itself, it is better to have the information read up and down rather than across, for the sake of comparison (University of North Carolina at Chapel Hill, 2018). Tables in a technical document or manual should not contain hundreds of cells of data and force the reader to sift through the numbers to draw a conclusion. The table should be concise enough that the reader can quickly and easily draw a conclusion for the data or find the information they were looking for.

2.4.4 VISUALS USED IN THE 3D PRINTER MANUAL

Figures, specifically photos and screenshots, were the predominant type of visual used in the 3D printer manual. The figures in each set of steps were not labeled because each figure clearly corresponded to each section of steps and labeling the figures seemed unnecessary and overcrowded certain parts of the document. The visuals were made large enough and spaced properly from each other to avoid crowding or distortion.

Tables were also used frequently in the manual, but not as a method of displaying data. The manual was created in Microsoft Word and tables were used for all of the required parts and tools sections as well as the steps sections. They provided consistent spacing and alignment for the text and visuals. The borders were simply made transparent for the sake of aesthetics. The tables used for these various purposes were also kept relatively small and did not span more than one page in most cases.

2.5 Technical Writing Methodologies

Over time various methodologies have been developed and adopted across the industry in technical writing. Structured authoring, for instance, is a publishing workflow that allows the writer to establish consistent formats and methods of organization throughout a document (O'Keefe and Pringle, 2017). Information Mapping is a documentation methodology that focuses on the structuring and visual style of the information in a document (Manuel, 2018). These are enforced through content rules that can pertain to anything from heading font to the number of items allowed in a bulleted list. These rules can be set in electronic documents using tools such as Microsoft office or Adobe Acrobat.

2.5.1 STRUCTURED AUTHORING

The backbone of structured authoring is elements. An element is a unit of content that can contain text or other forms of information. Elements can then be organized in a hierarchical fashion similar to how ingredients and steps are broken down in a recipe (O’Keefe & Pringle, 2017).

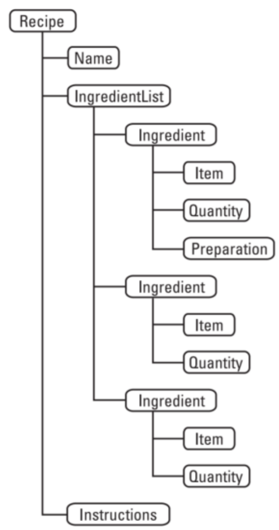


Figure 2: Hierarchical Tree

The structure of the tree in Figure 2 shows that the **IngredientList** is a child of the **Recipe** element and that the **IngredientList** child element contains the **Ingredient** child element. Each **Ingredient** element contains two or three child elements such as **Item** or **Quantity**. In an unstructured, formatted document, such as a word document, these relationships are implied by typography. Aside from heading styles, most word processors, such as Microsoft Word, do not capture or store the relationships in the tree. In structured authoring, in addition to storing the relationships between the elements, writers also store information about the attributes of certain elements. For example, under recipe, there could be asterisks with attributes such as author of the recipe and the type of cuisine.

2.5.2 INFORMATION MAPPING

Information Mapping is a type of structured authoring developed by Robert Horn, a Professor at Harvard and Columbia, in 1972. His goal was to understand how humans factor theory and other disciplines in order to improve learning (Information Mapping, 2017). From there Horn started Information Mapping Inc. and copyrighted the process. Information Mapping is made up of seven key principles:

- Chunking
- Relevance
- Labeling
- Consistency
- Integrated Graphics
- Accessible Detail
- Hierarchy of Chunking and Labeling

Chunking

The theory behind chunking is that "writers should group information into small, manageable units" (Manuel, 2017). A manageable unit is defined as no more than nine pieces of information. This is based on the "seven plus or minus two rule". This rule states that most people can only remember 5-9 pieces of information at any given time (Ferster, 2017). Information Mapping dictates that this rule should be applied to all different levels of documentation. For example, a manual should have no more than nine chapters, or no more than nine items in a bulleted list (Manuel, 2017).

Sticking to five to nine pieces of information is not always practical, however, the main idea is that human short-term memory is limited, so if users are actually going to retain information, chunking and multiple small digestible pieces of information is preferable (Moran, 2016). Chunking can also help with visual style and readability, so readers can quickly scan the document for main points and prevent large intimidating blocks of text (Moran, 2016).

In terms of relevance, Information Mapping says that “writers should make sure that all the information in one chunk relates to one main point based on that information’s purpose or function for the reader” (Manuel, 2017). One chunk should only contain one type of information. For example, instructions and descriptions should not be mixed in a chunk. Both types of information are necessary for a manual, but they serve different purposes and because of this should be in separate chunks.

For the sake of organization, chunks should be grouped into larger chunks and labeled accordingly (Byrd, 2003). Many proponents of Information Mapping believe that the label should be to the left of the block of information and word-wrapped within the label column (Manuel, 2017). This rule is not mandatory or crucial to the document. Labels can also be normal headings and stretch into the content column if necessary. Labels in the realm of Information Mapping essentially translate to headings, however, Information Mapping will usually contain many more labels than technical document would contain headings.

Consistency

The methodology for consistency states that for “similar subject matters, writers should use similar words, labels, formats, organizations, and sequences” (Manuel, 2017). The three levels in which consistency is particularly important are language, format, and structure. Maintaining consistent language throughout a document or set of documents helps the user become accustomed to the type of language used and will not force them to decipher the text or look up words or phrases. Using interchangeable words or phrases throughout can cause the user to decide for each use of the word, whether the meaning is the same. This increases the time it takes to assimilate information and use the document. Consistency in format and structure, such as headings, font size, and typeface can also allow a user to find the information they are looking for quickly even if they have never read the specific document but are familiar with the style and consistency of structure. If the document is procedural, for example, every user document should contain the same information, at the very same point, with all the same labels and headings.

2.5.3 STRUCTURED AUTHORING USED IN 3D PRINTER MANUAL

Microsoft Word was used in order to create this manual so the number of tools available to employ structured authoring were limited. The heading styles and tables were the most commonly used examples of structured authoring in the manual. There is a specific type of heading used for each chapter title, the required parts and tools sections, the steps section, and the title of each sub-step. This created the sort of hierarchical tree discussed above. Also, by using the heading styles in Microsoft word to create custom headings and alter previously existing headings, certain headings were able to be automatically included in the table of contents while others were not.

Each picture used in every section, whether it was the required parts and tools sections or the steps sections, were kept at consistent sizes based on the specific section. Every picture was also evenly spaced from each other in order to ensure that the proper amount of white space was provided for the sake of aesthetics and to prevent overcrowding. Every chapter was also structured the same. The format that I decided on was:

- Required Parts
- Required Tools
- Section Overview Paragraph
- Steps

This not only maintained the consistency of the document, but also made it much easier to write. Once I decided on this format I could copy and paste it into every chapter and just change the pictures and text in the steps section. Overall, this made the writing process much easier.

2.6 3D Printer Build Manuals

Although the purpose of the manual discussed in this report is to help users build their own 3D printers, it is important to look at the manuals that the industry leaders have produced. Prusa and Ultimaker are two of the largest 3D printer manufacturers in the industry. These can serve as examples of best practice 3D printer manuals and contain elements of which the manual created for this project is based on. In all other forms of writing, such as essays or novels, authors often draw their inspiration from and base their work off of other critically acclaimed author’s projects. This also applies to manual writing, which is why the Prusa and Utlimaker manuals are examined in this chapter.

2.6.1 PRUSA 3D PRINTING HOW-TO GUIDE

Prusa provides online assembly how-to guides for all their printers and other accessory kits written by users themselves. The reason why Prusa refers to this as “how-to guide” and not a manual is mainly because it is not a traditionally published manual. It is interactive and published online. This how-to guide is also influenced and even altered by the users themselves, whereas manuals generally have a handful of authors at most.

The how-to guides for the Prusa MK3 is broken down into eight main sections. From there, other users vote the best manual for each section and that is the one that Prusa makes accessible. Each section begins with basic information such as the difficulty level of the section’s assembly, the number of steps in the section, the estimated time required for the assembly, and the tools that will be needed. For each step in a section, pictures and colored arrows are used with color corresponding bullet points with brief explanations about the task. Included in certain steps are also notes which provide additional information or warnings made noticeable by using red text and a consistent hazard symbol (Dolezal, 2017). Figure 6 shows an example of this. Many steps also have multiple pictures that users can look through that provide different angles. For the sake of feedback, users can leave comments on each step that aid the author in editing the manual or provide help for other users.

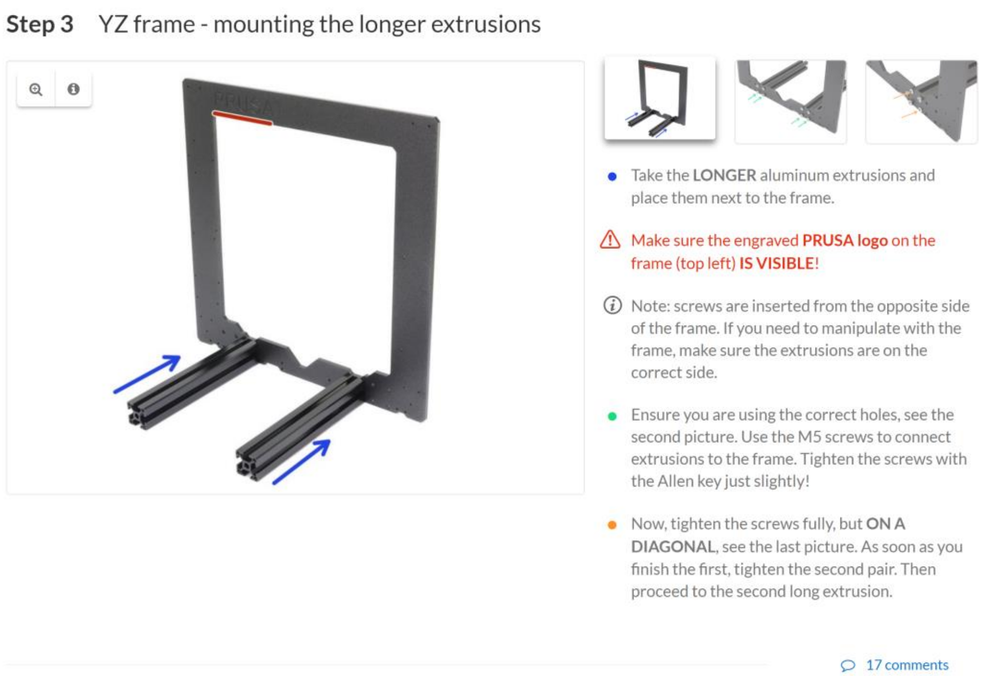


Figure 6: Step 3 of Assembling the Y-Axis

Overall the author follows many of the traditional rules for manual writing. For example, in each of sections, the headings, visuals, and text are all kept consistent. The author also limits the amount of text used and makes sure that the text that is used is clear and easy to understand. Some of the sections have upwards of forty steps, which may seem like a lot to the user, however, it is virtually impossible to limit the number of steps in a manual for a build process of this magnitude. The seven plus or minus two rule is useful, but in some cases, especially in manual writing, it is impossible to follow. It is simply not worth limiting the number of steps just to follow a general rule of thumb. Having eight initial sections to start with does make the manual seem less intimidating. It almost hides how many steps there really are so the user may not notice until they are already well into the build process and less likely to be deterred.

2.6.2 ULTIMAKER USER MANUAL

Ultimaker, another leader in the 3D printing industry, also provides an online manual for their printers. Ultimakers printers are fundamentally different from the Prusa printers and, as a result, so are their manuals. Ultimaker printers arrive to the user's home almost entirely assembled, while Prusa printers arrive in pieces and require a full assembly. The Ultimaker online manual is simply a PDF and not an interactive website. The "Get Started" section is the only section that focuses on any sort of assembly and only accounts for a total of five pages out of thirty two (Ultimaker, 2015). These five pages include multiple pictures and a list of the various parts included. Following those pictures are multiple paragraphs, each accompanied by a pair of pictures with numbered steps for installing the spool holder, glass print plate, and the power supply. The rest of the manual focuses on how to operate the printer and perform maintenance on it, if necessary (Ultimaker, 2015).

When turning on your Ultimaker 2, you will always see the Ultimaker logo first after which you will go to the main menu. The main menu offers three options: PRINT, MATERIAL and MAINTENANCE.

PRINT
The "Print" menu simply allows you to select one of the print files from the SD card and will automatically start the print after that.

MATERIAL
In the "Material" menu you can either change the filament on your Ultimaker 2 or change the settings of material profiles. When selecting "Change" the Ultimaker 2 will start the procedure as described in chapter 3. In the "Settings" menu you can select material profiles and change their settings in the "Customize" menu.

MAINTENANCE
The "Maintenance" menu offers various options. By selecting "Build plate" you will be guided through the bed leveling steps. In the "Advanced" menu several options can be selected in order to manually do certain actions or change machine settings. Below a short overview of all these options is shown.

- LED settings — Change the settings of the LED lights in your Ultimaker 2
- Heatup nozzle — Set custom temperature to manually heat up the nozzle
- Heatup buildplate — Set a custom temperature to manually heat up the heated bed
- Home head — Homes the head in the left back corner of the Ultimaker 2
- Lower buildplate — Moves the build plate to the bottom of the Ultimaker 2
- Raise buildplate — Moves the build plate to the top of the Ultimaker 2
- Insert material — Heats up the nozzle after which you can insert filament
- Move material — Heats up the nozzle after which you can use the scroll wheel to forward the material
- Set fan speed — Set the speed of the two fans at the sides of the print head
- Retraction settings — Customize the settings for retraction
- Version — Shows the current firmware version on the Ultimaker 2
- Runtime stats — Shows for how much time the Ultimaker 2 has been on and printing
- Factory reset — A complete reset of your Ultimaker 2 through which you can completely recalibrate it

FINE-TUNING
The Ultimaker 2 also offers you the possibility to fine-tune settings during the printing process. This allows you to get full control over the printing process and helps you achieving the best print results. You can do this by accessing the "Tune" menu during printing. The Tune menu basically shows you the same settings as in the Advanced menu, which means that you can change settings like for example the temperature and speed of printing. Furthermore, it is possible to select "Pause", after which you can change the filament in the middle of a print and resume again.

Figure 7: Ultimaker Text Usage

This manual is significantly shorter than the Prusa manual and the purpose is more for operation and setup rather than an in-depth step-by step assembly guide. Because of this, it is almost more of an operator's manual than a user manual at all. The Ultimaker manual does follow the main principles of manual writing in terms of consistent structure and visual use. However, this manual is much more text heavy and there are some areas that could be overcrowded or difficult to read. This can be seen in Figure 7 above.

2.6.3 SIMILARITIES BETWEEN 3D PRINTER MANUAL AND PRUSA HOW-TO GUIDE

Prusa's online how-to guide for its 3D printers is clear and easy to use. It is broken down into sections and at the beginning of each section lists the necessary tools and parts that will be required to complete the section. Each step is then broken down with pictures to the left and color coated sub-steps to the right. The color of the bullets next to the sub-steps correspond to the colored arrows or visual aids used for instruction in the visuals.

The 3D printer manual written for this MQP utilizes a similar format of listing the necessary parts and tools at the beginning of each chapter and provides visuals next to each sub-step. The formatting of the manual written for this MQP is slightly different than the Prusa manual formatting, but the main difference is the amount of context that is provided. The 3D printer manual written for this MQP has descriptions of each chapter at the beginning and a few sentences of context before each sub-step. The context before each sub-step explains the significance of the sub-step, how it relates to the whole printer, or how it ties in to previous steps. This context was provided to help the user not lose sight of the higher-level importance of the steps and avoid potentially making a mistake that would need to be fixed later in the assembly process.

2.7 Focus Groups

One way to know whether a user manual is effective is to receive feedback from the users on their experience. One method of collecting feedback on a product is to conduct focus groups. Focus groups are moderator guided discussions of approximately six to ten people. The moderator asks questions directly related to users' experiences with the product and ensures that the conversation stays relevant and on topic. The data collected from the focus group can be recorded either by taking notes or by using a recording. From there, the data can be analyzed and used to improve the overall quality of the manual.

2.7.1 PURPOSE AND STRUCTURE

The first step in organizing a focus group is for the author of the manual to articulate what it is that they expect to gain from the focus group research (Breen, 2006). Once the author has been able to state what they hope to gain from the research, they can then derive their research questions from these written statements. These research questions will determine whether the focus group itself is actually necessary (Krueger, 2017). If any of the research questions require comparisons of users' experiences or the need to discover behavioral trends among user experiences then a focus group is the proper course of action (Breen, 2006). If this is not the case, for some reason, then secondary research such as journal articles or books should suffice.

Once the research questions have been determined, it is important to define the characteristics of the focus group. A focus group can be anywhere from six to ten people (Eliot & Associates, 2005). The main idea is that the group is large enough to facilitate productive conversations, but not too large that some participants are left out. Focus groups can last anywhere from forty-five minutes to an hour and a half, but any longer than an hour and a half generally results in the participants experiencing burnout and an overall less productive focus group (Eliot & Associates, 2005). One focus group alone is also never enough to yield valid results on a topic. In order to reach a consensus on a topic usually three or four focus groups are needed. The content of the questions for focus groups are important and should be considered carefully before arranging the first focus group.

2.7.2 QUESTION TYPES

One of the most important aspects of focus group questions is for it to be open-ended (Krueger, 2002). Any question that can be answered with a “yes” or “no” can potentially halt the conversation and negatively impact the flow of the focus group. There are three main types of focus group questions that help facilitate conversations (Eliot & Associates, 2005):

- **Engagement questions:** Engagement questions introduce participants to the topic of discussion and help them get comfortable in the setting.
- **Exploration questions:** ask specifically about the desired research questions rather than asking participants about their personal experiences and how they compared to others’ in the group.
- **Exit questions:** Exit questions ensure that participants do not have any further questions or feedback and that they were comfortable with how the focus group was conducted.

In a focus group for a 3D printer, for example, an engagement question might be “Have you ever used a 3D printer before?” and an exploration question could be “Does this 3D printer meet your expectations for how a 3D printer should perform?” (Eliot & Associates, 2005). Overall the focus of the questions should move from general to specific (Krueger, 2002). This is the responsibility of the moderator.

2.7.3 THE MODERATOR

The moderator of a focus group plays a key role in the viability of the data collected. An effective moderator needs to be able to exercise control over the group without making any of the participants feel obstructed or silenced (Krueger, 2002). The moderator does not necessarily have to be the author themselves, but they, at the very least, need to have adequate knowledge of the discussion topic. A moderator that is not the author is actually beneficial because it can prevent any unintentional leading of the participants that could potentially occur if the author is the moderator. Assistant moderators are commonly used for the purpose of helping to prepare the moderator, as well as taking thorough notes during the focus group and setting up recording equipment (Krueger, 2002). It often helps for the moderator to give verbal and non-verbal cues throughout the discussion, and probe participants to further explain themselves if necessary. Active listening techniques such as summarizing participant's long or ambiguous comments not only makes participants feel as though their comments are being valued, it also clarifies the comment for the rest of the group (Eliot & Associates, 2005). Once the appropriate amount of focus groups have been conducted the data is ready to be compiled and analyzed.

2.7.4 APPLICABLE ELEMENTS FOR 3D PRINTER FOCUS GROUP

I conducted a focus group for the 3D printer manual because it seemed like the most effective method of obtaining user feedback given the resource and time constraints of the project. The research questions and logistics of the focus group are discussed further in the Methodology section of the report. While designing the focus group for the 3D printer manual, it became clear that the focus group was going to need to be more interactive rather than just a question and answer session. The Exploration Questions above are intended to obtain feedback directly related to the research questions of the focus group. However, it was difficult for users to answer those types of questions without ever having used the manual. This led to the users being asked to perform tasks using the manual so they could better understand it and provide more constructive feedback. These interactive tasks are described in detail in the Methodology.

I served as the moderator of the focus group because I believed that it would be more helpful to the users to have the author present to answer questions about the manual since they were using the manual to perform specific tasks. Although it was not ideal that I was the moderator, I did my best to remain unbiased and avoided leading the participants.

3. Methodology

The manual written for this project was developed using the technical writing best practices that were determined through the research presented in the background chapter. The full manual can be found in Appendix A. This chapter focuses on the purpose and format of the focus groups that were conducted in order to receive feedback to improve the manual. It also serves to shed light on any areas where technical writing best practices could have been better implemented and areas where the users actually did not prefer certain best practices.

3.1 Purpose and Structure of 3D Printer Manual Focus Group

For this manual it was important to conduct focus groups rather than one-on-one interviews because the goal was to obtain feedback and information that was applicable to most users regarding the manual itself and determine user feedback on best practices used in the document. After determining that a focus group was the best method of primary research for this project it was then necessary to target the desired participants for the focus group. Since this project focuses on building a 3D printer from scratch, the target audience of the manual is engineering students or 3D printing hobbyists with technical backgrounds. Without some sort of technical background, it is challenging to build a 3D printer, even with a manual. Based on the target audience, the participants selected for the focus group were all engineering students.

A total of three focus groups were conducted, with three participants in each group, all of whom were student volunteers. The focus groups were limited to three participants per group since the participants could only complete the tasks one at a time and this proved to be too time consuming for a large group. The focus groups lasted around forty-five minutes in order to allow the participants to remain focused and engaged. Every focus group discussion and interaction was also audio recorded in its entirety. The basic research questions that the focus groups aimed to answer were:

- Was this manual helpful in explaining the selected tasks for building a 3D printer?
- Do users prefer to use manuals for large construction projects, or work through the project on their own?

3.2 3D Printer Focus Group Questions

In order to answer these questions, a focus group procedure was created which can be found in Appendix B. The procedure started off with an explanation of the topic of the focus group and some basic guidelines that involved the participants giving their consent to be recorded and an agreement to engage in respectful and civil discussion.

3.2.1 ENGAGEMENT QUESTIONS

The first round of questions that were asked were introduction engagement questions, based on Eliot & Associates' format for focus groups (Eliot & Associates, 2005). Some examples of the engagement questions asked were "what is the last product you purchased that included a manual?" and "when is the last time that you used a manual to assemble something?". These engagement questions help the participants to begin thinking about the topic of the focus group, but also allow for personal anecdotes and more casual conversations.

3.2.2 INTERACTIVE QUESTIONS

The interactive questions asked the participants to get involved and use the manual to perform various instructional tasks outlined in the manual. Due to time, cost, and resources it was not possible to have every participant build their own 3D printers using the manual. Instead specific steps from the manual were chosen for the participants to perform. Two tasks that were chosen were attaching a limit switch and wiring the NEMA 17 Motors to their correct location on the RAMPS 1.4 board. One of these tasks, attaching the limit switches, was relatively simple. The only steps involved were attaching the limit switch to its mount using screws and nuts and then press fitting the mount and limit switch onto the printer (see Appendix A. Manual Chapter 8). However, connecting the NEMA 17 Motors to the Arduino Board was less intuitive and very difficult to accomplish correctly without the use of the manual. In both scenarios the participants were given the task first and then given the manual with no further instruction. The purpose of this was to see, without being prompted, if users would choose to follow the steps in the manual.

3.2.3 EXPLORATION QUESTIONS

Following the interactive tasks, the participants were asked Exploration Questions about the clarity of the directions provided and their opinions on using a manual for those types of tasks. The following are some of the Exploration Questions I asked:

- Would you have preferred more or less text in each step and why?
- What about the visuals could have been improved?
- Did you feel more inclined or less inclined to use the manual when first given the tasks and why?

- Do you feel confident that you could build a 3D printer using this manual, based on the tasks you completed, and if not, what would you change?

The rest of questions can be found in the focus group procedure in Appendix B. Following the main discussion, the participants were asked exit questions about whether or not they felt anything was missing or left out of the discussion and if they had any questions or concerns about the focus group.

4. Focus Groups Results and Analysis

The focus groups provided valuable feedback regarding how the manual could be improved, shed light on areas where best practices could have been better implemented, and, in some cases, showed that what users prefer is not always in agreement with technical writing best practices. Three focus groups were conducted with three participants in each group for about forty-five minutes. Typical focus groups are somewhat larger, however, because of the amount of time that each interactive task required, it made the most sense to have smaller groups and prevented the participants from becoming burned out or frustrated. Even though the participants were only given two tasks to perform from the manual, their feedback was pertinent to the entire manual.

4.1 Feedback on the 3D Printer Manual

Overall, most of the participants had either bought a product that contained a manual or used a manual itself somewhat recently. This just goes to show that even with other tutorial options such as videos and wiki guides, manuals are still one of, if not the most prevalent form of instruction for consumer products. Overall, users were satisfied with the amount of text that was used. Two users commented that they would prefer just a sentence or no words at all, similar to an IKEA manual, which only contain pictures and visual directions.

Eight out of the nine participants in the focus groups commented on the use of visuals in the manual. The consesnsus was that in both the limit switch chapter and the wiring chapter (see Appendix A for full manual) that there needed to be larger pictures and more of them. One participant even commented that “it is okay if the picture takes up most of the page as long as it clearly shows the step that needs to be performed.” Some of the more specific comments were that in the limit switch chapter the limit switch and the limit switch mount were both shown in the required parts section, however, only the limit switch mount was shown attached to the printer in the steps. There was a clear disconnect between attaching the limit switch mount to the printer and first attaching the limit switch to the mount and then attaching both to the printer. This was a relatively simple fix and only required one or two more steps detailing how to attach the first limit switch to its mount and then showing the limit switch and the mount attached to the printer.

Most participants had less trouble following the directions in the wiring diagram section. Their task was to connect the wires from the Y motor to their corresponding pins on the RAMPS 1.4 board. The diagrams in the chapter were drawings of the layout of the RAMPS 1.4 board with the 4 pins outlined with a box where the Y motor was supposed to be connected. Two of the participants stated that while the directions were clear, and they knew that they needed to connect the wires to the outlined box in the diagram, they were confused when they looked at the actual RAMPS 1.4 board compared to the diagram. This was solved by including an actual picture of the RAMPS 1.4 board with the correct pins circled, rather than relying on a drawing.

As not only the author of the manual, but also the designer and builder of the printer, my biggest challenge was trying to understand the manual from the user's perspective. I might believe that its self-explanatory that the limit switch should be attached to the limit switch mount before being installed on the 3D printer, however, it is not as clear for someone with little prior knowledge of limit switches or 3D printers.

4.2 Application of Focus Group Feedback to 3D Printer Manual

This manual was written based on technical and manual writing best practices determined through literature review, which can be found in chapter two of this report. However, it was gathered from focus group feedback that there were areas that the best practices could be better implemented, or were not implemented at all, and some of these were pointed out by participants in the focus group.

One instance was the spacing and proximity of the pictures in the steps. A participant stated that not only were the pictures too small, they were also too close together, which made the steps feel crowded and difficult to follow. One of the most important elements of technical writing is the proper use of proximity and white space, as discussed in section 2.4.1. The amount of spacing in between visuals is up to the discretion of the author, but it must be enough to avoid overcrowding. Once that amount of space is decided on it must be kept consistent throughout the entire manual. The use of proximity and consistency was used in the required parts and tools sections, however, it needed to be improved upon for all steps throughout the manual.

Another best practice for user manuals is to avoid the use of jargon, which was discussed in section 2.2.1. Having designed and built the printer myself, one of the challenges I faced was to determine what was considered jargon. For example, although all of the focus group participants were engineering students, the majority of them were not familiar with what an endstop was and some even asked that I use a non-technical term for endstop. Even though a picture of the endstop was provided in the required parts section and labeled as an endstop, users still found it to be jargon, whereas I did not. This is a result of my bias as both the designer of the 3D printer and author of the manual. Another example of jargon that confused many users, was the metric screws being labeled as “M3” or “M6” screws meaning either 3-

millimeter or 6-millimeter diameters. This problem was easily solved by simply defining the abbreviation in the beginning of the manual.

4.3 Users' Requirements in Comparison with Best Practice Requirements

There were a few instances during the focus group in which the users input directly conflicted with some of the technical writing best practices discussed in the literature review. One example of this was the seven plus or minus two rule. This rule states that people can generally only remember and process five to nine pieces of information at once. One user in particular said that they would have preferred more pictures overall or even a manual made up of entirely pictures and no text. While I agreed that certain manuals have had success with that style, this could result in quite a few pictures per section and even per step, perhaps negatively impacting the readability of the manual. The participant responded by saying it did not matter how many steps or pictures there were, as long as the directions were as clear as possible. Including as many steps and pictures as possible would most likely violate the seven plus or minus two rule. For each section, the manual contains a maximum of four to eight steps, and a maximum number of four to nine pictures per steps section, in an effort to abide by the rule. The reason why I made an effort to follow the rule is because even though some users said they would prefer as many pictures as possible, that simply would not be practical for the sake of writing a manual. It would be difficult to produce an organized and readable manual with so many pictures. Following the seven plus or minus two rule even somewhat closely ensures that there isn't too much content to be useful.

The seven plus or minus two rule is generally a helpful rule of thumb, but as seen in the exchange above, for some users technical writing rules such as this one are not necessarily applicable or best when writing for users. The most important qualities of a technical document for average users are clarity and simplicity. It does not matter if that is accomplished with more than nine steps as long as it is as easy as possible for the user to understand.

In some cases, like IKEA, or even in Prusa's online how-to guide for their 3D printers, there is very little or even no text used. Traditional manual writing for years has dictated that instructions be broken down into numbered steps with text and pictures. However, some companies have found that different formats are better for certain user bases. There can be a disconnect between the academic aspect of technical writing and its purpose as an instructional aid for users. It is important to avoid the pitfall of blindly following best practices, rules, and templates when they are not always the best option for the user, depending on the product or user base.

A challenging aspect of writing a manual and product development in general is distinguishing between the feedback of an entire user base and that of an outlier. It is impossible to please the entire user base, and so, compromises have to be made. The feedback from the outlier is still valuable, but it needs to be carefully compared to the feedback of the entire user base before it can be implemented. There has to be a balance between implementing outlandish suggestions from only one or two users and writing and editing to cater to the majority of the user base.

Conclusion

The background research that went into this project was more than just a literature review, it was directly applicable when writing the 3D printer manual. My research on the purpose of a manual helped me to determine that my target audience for the manual was engineers and 3D printer hobbyists. It also helped me set attainable goals for myself and prevented the project from becoming too large in scope. Although a user manual was the type of manual that I ended up writing for the 3D printer, it was useful to learn about other types of manuals as well and the genre as a whole. Having the ability to do in depth research on how to outline a manual before actually writing one was also useful. Outlining the 3D printer manual was actually one of the most difficult aspects of the writing process but being able to draw on the knowledge I gained from sources like *PrismNet* and the *Handbook of Technical Writing* was crucial.

Knowing how to properly use visuals was fundamental in writing the 3D printer manual. The research gathered and analyzed in chapter 2 taught me the importance of keeping all visuals a consistent size with consistent spacing and borders. This was vital to the aesthetics of the manual. I was also unfamiliar with technical writing methodologies, such as structured authoring, before this project; however, structured authoring played a large role in creating a consistent format and flow throughout the entire 3D printer manual. Having the opportunity to also read through Prusa's and Ultimaker's manuals provided me with a sense of what different types of manuals already existed for 3D printers and how the industry leaders were writing their manuals. This experience greatly improved the overall quality of my manual.

Conducting focus groups is a valuable research method for any product development process and proved effective for obtaining feedback on the 3D printer manual. The feedback from the focus groups showed that there is a difference between writing for users and academic writing. An author can only write a manual to the best of their ability based on the research they have done and the training or education they have received. What the author believes is best for the user and what the user actually wants are not always the same thing. The user also does not always respond the way the author might expect and there will always be unforeseen issues that the author will not be able to uncover before user testing. Manual writing is a process of user testing and subsequent improvements and revisions until the manual is ready for release.

Appendix A. Manual

WORCESTER POLYTECHNIC INSTITUTE

Professional Writing Major Qualifying Project

An Instructional Manual for Building a DIY 3D Printer

By: Miles Nallen

CONTENTS

Preface

This preface defines the purpose of this manual and its structure. It also acknowledges the academic requirements of this manual. This is important so the audience can understand that this manual is not a for-profit manual nor produced by Worcester Polytechnic Institute as a University. This chapter also contains a link to the Google Site, which has resources such as SolidWorks files available for download and links to sources to buy parts for the printer.

Academic Requirements

The design and construction of the 3D printer discusses in this manual was completed to fulfill the Major Qualifying Project requirement for Mechanical Engineering majors at Worcester Polytechnic Institute. The goal of this project was to build a 3D printer from scratch that could then be modified to generate a magnetic field with the end goal of printing permanent magnets. The documentation and subsequent creation of a user manual for this process was for the fulfillment of a Major Qualifying Project for the Professional Writing major at Worcester Polytechnic Institute.

Manual Purpose

The purpose of this manual is to aid first time 3D printer builders in assembling their own 3D printer. Each chapter in this manual contains step-by-step directions, as well as pictures of the parts needed for the section and the list of tools needed. Some of the brackets and supports used in this manual were 3D printed. The SolidWorks files are provided for download on the Google Site, and screenshots of the parts can be found in their corresponding sections of the manual and in Appendix B.

Manual Audience

The intended audience for this manual is engineers or experienced 3D printer users with technical backgrounds. This is primarily because of the use of SolidWorks, electrical wiring, and coding needed to complete this project. First time hobbyists with little to no technical experience or 3D printer experience may want to start with a 3D printer kit first.

SolidWorks Files

The 3D printer discussed in this manual was designed and built by three mechanical engineering students. As a result, some of the parts were custom and had to be 3D printed. All of these parts should be 3D printed before building the printer to avoid confusion and ensure that all of the necessary parts are obtained before beginning the build process. All the SolidWorks files are available for download on the Google site. SolidWorks must be downloaded and installed in order to open and modify these parts. A list and pictures of all the parts that need to be 3D printed can be found in Appendix B.

Google Site

The manual can be viewed on the Google Site itself or downloaded and viewed separately as a PDF. There is a total of three pages on the site:

- The Manual Page – Contains a viewable copy of the manual as well as a PDF copy available for download.
- The Part Sources Page – The part sources page has the entire Bill of Materials for the printer and links to buy each part, most of which are for sale on Amazon.
- The SolidWorks File Page – The SolidWorks page contains all the necessary part files for download that are mentioned in the manual.

The link to the Google Site is the following:
sites.google.com/s/1qQHvO8y2WTTtrM5rZ5vY47ciejsf9TQw/p/1av8OMEKtIdAtXqcz6VTaPknvYxqdwwR2/edit

Chapter 1: Introduction

The purpose of this chapter is to gain a higher-level understanding of the build process and of the functions of each part. This chapter also contains background information on the inspiration behind the printer, some of its advantages, as well as steps that need to be taken before building can begin. In the process overview diagram, each part references a chapter later in the manual which contains step-by-step instructions, pictures, part lists, and the necessary tools required to complete the specific assembly. The instructional portion of the manual starts in Chapter 2.

3D Printer Background

The team of engineers that designed and built this 3D printer drew inspiration from a variety of DIY Youtube videos, other custom builds on websites like Thingiverse, but mainly from RepRap. RepRap is an opensource 3D printer, in which almost all the parts can be 3D printed. This 3D printer was designed with a similar concept in mind. The goal is for you to be able to 3D print a lot of the parts yourself. This lowers the cost and eliminates shipping time or finding a vendor for certain parts. This 3D printer was also designed to be relatively easy to build. All of the engineers who worked on this project were relatively new to 3D printing prior to this project, so this printer was built by beginners for beginners.

Pre-build Preparation

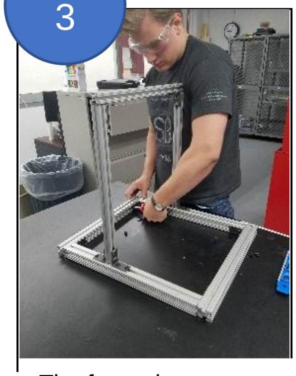
Before any building can commence, it is important that you have purchase all the necessary parts before you begin building the printer. The bill of materials in Appendix A contains all the parts, prices, and links for where to purchase each part can be found on the Google Site. However, it is important that if you decide to purchase a part from a different source that you carefully vet the source and read previous users' reviews and experiences.

PROCESS OVERVIEW

Chapter 2

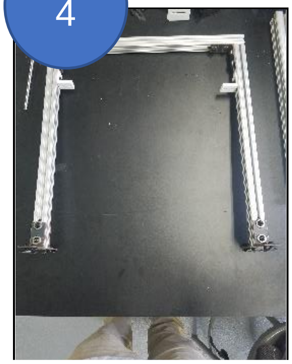
The heatbed is the surface that plastic is extruded onto. It is crucial because when extruded plastic is cooling it will warp on the edges if it does not cool and shrink evenly.

Chapter 3



The frame base provides structure for the HeatBed Assembly and the YZ frame. It is made up of four 12-inch pieces of 8020 aluminum stock.

Chapter 4

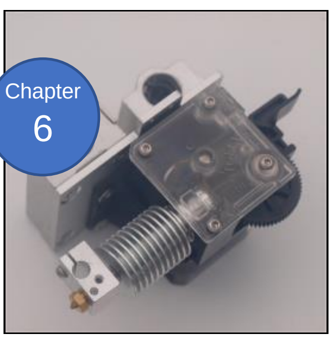


This frame is crucial to the overall integrity of the machine since it supports the vertical smooth and threaded rods that drive the extruder up, down left, and right, and the carriages that guide the smooth and threaded

Chapter 5

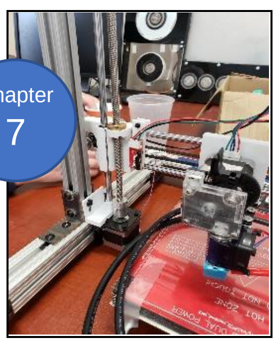
5 NEMA 17 Motors are used on this 3D printer to drive the heatbed back and forth, as well as to move the extruder up and down.

Chapter 6



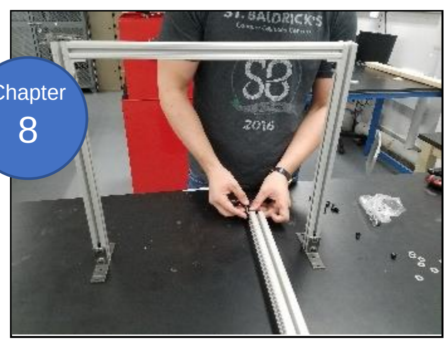
The extruder itself is what lays down heated plastic material on to the heatbed layer by layer to create 3D objects.

Chapter 7



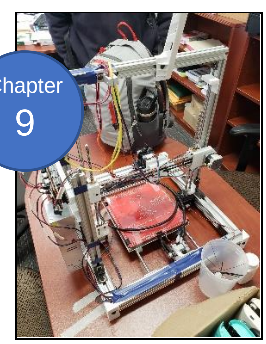
The YZ and X carriages hold the smooth and threaded rods in place, as well as the pulleys that much of the movement of the machine relies on.

Chapter 8



The cross bar attaches across the top of the two pieces of the YZ frame. The main purpose of the cross bar is to ensure that the two pieces of the YZ frame do not bow inward due to resulting forces of the machine running.

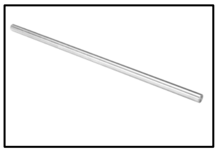
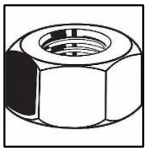
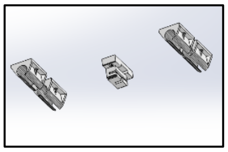
Chapter 9



The power supply is 12 volt and supplies energy to the Arduino Board, NEMA Motors, heatbed, and extruder.

Chapter 2: Heatbed Assembly

Required Parts

			
4x WINSINN Leveling Spring M3 Screw Knobs	PCB Heatbed	4x LM8UU Bearings	8mm Diameter Smooth Rods
			
8x M3 (3 Millimeter) Nuts	8x M3 Nuts	3D Printed Bearing Holders and Belt Holder	Heatbed Mount Plate for Bearings and Smooth Rods

Required Tools

		
Metric Thread Tap Kit	Epoxy	M3 Hex Key

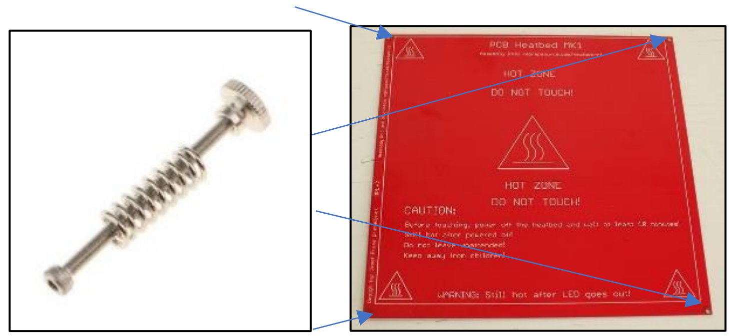
The heatbed is the surface that plastic is extruded onto. It is crucial because, when extruded plastic is cooling, it will warp on the edges if it does not cool and shrink evenly. The heatbed supplies a consistent and evenly distributed temperature for parts to cool on. The heatbed itself is aluminum because of its desirable thermal conductance properties, which ensure even heat distribution. It is heated by a thermistor, which is connected to the 12-volt power supply.

Steps

1. Attaching the Heatbed to the Aluminum Plate

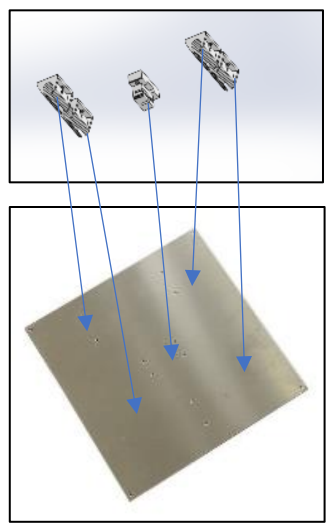
The heatbed is attached to the aluminum plate using level spring screw knobs that allow the level of the heatbed to be changed at each corner.

1. Attach the heatbed on top of the aluminum plate using WINSINN Leveling Spring M3 Screw Knobs. There are four holes at each of the corners of the heatbed and aluminum plate. Each of the four screw knobs should be inserted through each corner hole to connect the two plates.



2. Attaching the Bearing Holders and Belt Holder to the Aluminum Plate

The bearing holders hold LM8UU bearings that the smooth rods slide through. The belt holder holds the end of the belt allowing a loop to be formed around the NEMA motor so the heatbed can move back and forth

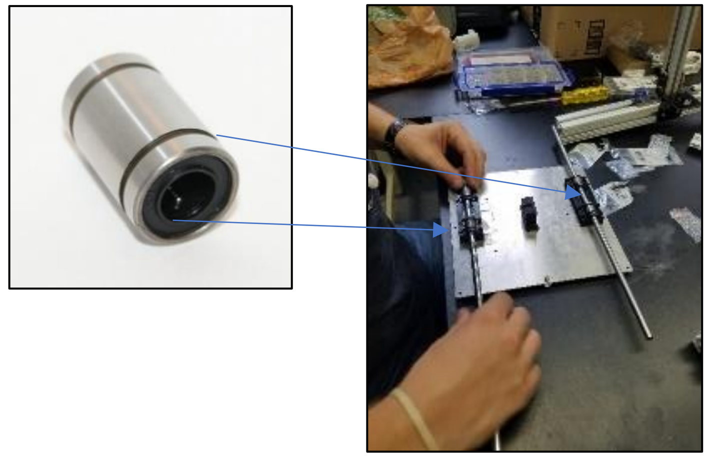


1. Attach the four 3D printed bearing holders to their corresponding holes on the aluminum plate using M3 screws and nuts.

   Note: If for some reason the aluminum plate does not come with holes already tapped, the hand tapping kit can be used to tap holes or epoxy can be used to attach the smooth rod and belt holders.

2. Attach the belt holder in between the 3D printed bearing holders. Attach using one of the two methods mentioned in the previous step.

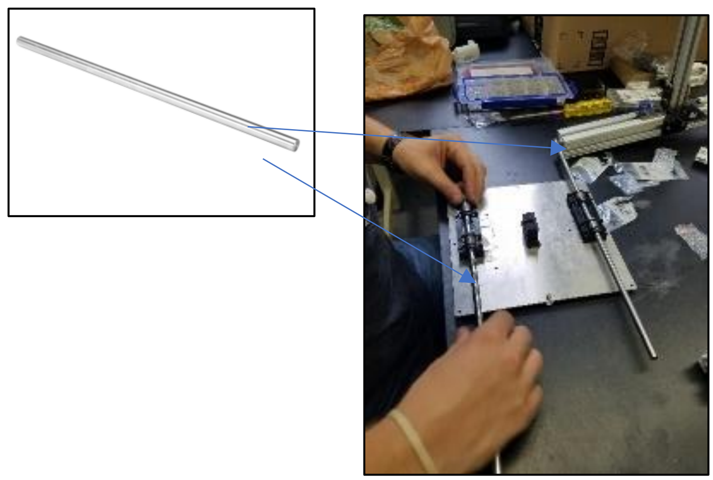
3. Inserting the Bearings



Four LM8UU bearings are inserted into the 3D printed bearing holders. The smooth rods are then slid into the bearings. There should be little to no friction and the rods should be able to slide back and forth easily in the bearing.

1. Insert the bearings into the bearing holders. The bearings should fit snug in the holders; however, if they are sliding back and forth, they can be held in place with epoxy.

4. Inserting the Smooth Rods



The smooth rods allow the heatbed to move back and forth.

1. Insert the two smooth rods through the pairs of bearing holders on either side of the aluminum plate. The rods should be to able slide easily in the bearings.

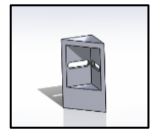
Chapter 3: Frame Base Assembly

Required Parts

30x ¼-20 Inch Screw with Standard T Nut

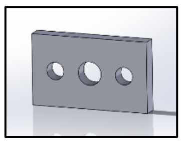
4x Hole Inside Corner Gusset Corner Bracket

4x 12-Inch Aluminum 80/20 Stock

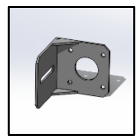


4x 3D Printed Frame Base Feet

Assembled Heatbed (from last step)

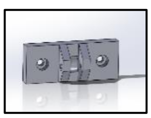


4x 3D printed smooth rod holders



1x 3D Printed NEMA Motor Mount for Y Movement

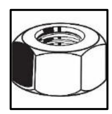
2x NEMA Motor Mounts for Z Movement



3D Printed Y Movement Pulley Mount

GT2 3mm Bore Aluminum Toothless Timing Belt Idler Pulley

1x M3 Screws



1x M3 Nut

Required Tools

¼-20-inch Hex Key

The frame base provides structure for the Heatbed Assembly and the YZ frame. It is made up of four 12-inch pieces of 8020 aluminum stock. The 8020 aluminum stock is slotted and allows for L brackets and other various mounts to be attached to the base using screws and T nuts. The 3D printed feet provide increased stability when the machine runs and lifts it above the surface it is operating on.

Steps

1. Attaching the Y NEMA Motor Mount

The Y NEMA Motor mount supports the Y NEMA motor. It should be attached in the center of a 12-inch-long piece of aluminum 8020 stock.

1. Attach the 3D Printed NEMA Motor mount for Y Movement to the center of 1 Piece of aluminum 80/20 stock using ¼-20 screws and T nuts.

2. Attaching the Smooth Rod Mounts

The smooth rod mounts hold the smooth rods and heatbed in place. The mounts use a press fit design, so the rods fit snuggly in the mounts and do not move.

1. Attach two 3D printed smooth rod mounts exactly 2 inches from either side of the NEMA motor mount for the Y movement. Use ¼-20-inch screws and T nuts for this task.

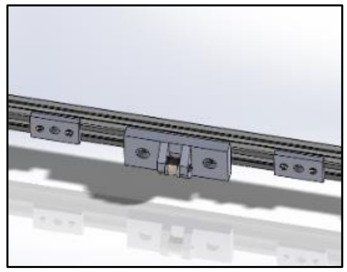
3. Attaching the Z NEMA Motor Mounts

The two Z NEMA motor mounts support the two NEMA motors required to move the extruder up and down in the Z direction.

1. Attach the 2 NEMA Motor mount for Z movement in the center of two of the remaining pieces of aluminum 80/20 using the same screws and T nuts used in the previous step.

   Note: The orientation of these mounts is different than the one in the previous step.

4. Attaching the Smooth Rod Mounts and Pulley Mount



The last piece of aluminum 8020 stock that has not been altered will be used for the 3D printed Y movement pulley mount and opposing smooth rod holders. The pulley and pulley mount are for the belt that drives the heatbed back and forth in the Y direction.

1. Attach the 3D printed pulley holder in the center of 12-inch-long piece of aluminum 8020 stock. Use ¼-20-inch screws and standard T nuts.
2. Place the GT2 Smooth Pulley in the center of the pulley mount. Slide an M3 Screw through the hole in the pulley and secure it on the other side with the M3 nut.
3. The 2 remaining smooth rod holders should be installed on either side of the pulley holder, exactly parallel with the two on the opposite piece of stock. Use ¼-20 inch screws and standard T nuts.

Chapter 4: XZ Frame and Full Frame Assembly

Required Parts

24x ¼-20 Inch Screw with Standard T Nut

6x Hole Inside Corner Gusset Corner Bracket

3x 12 Inch Aluminum 20/20 Stock

Required Tools

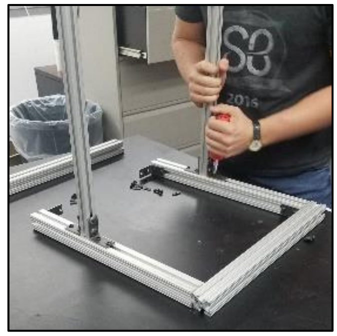
¼-20-Inch Hex Key

The XZ frame is made up of two pieces of aluminum 2020 stock. This frame is crucial to the overall integrity of the machine since it supports the vertical smooth and threaded rods that drive the extruder up, down, left, and right, and the carriages that guide the smooth and threaded rods. If the XZ frame is not carefully measured and installed it can adversely affect the functionality of the entire printer. Once the XZ frame is attached the rest of the base frame can be assemble and the entirety of the frame, aside from the cross bar, is completed.

Steps

1. Assembling the XZ Frame

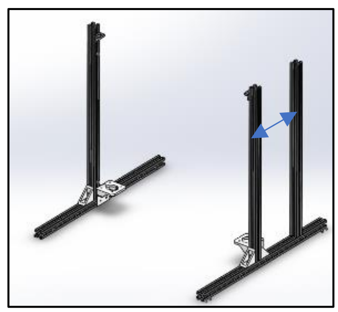
The XZ frame provides support for the smooth rods, threaded rods, and the carriages that hold them. It is crucial to the structural integrity of the printer.



1. Attach two of the aluminum 2020 pieces of stock, standing vertically, adjacent to the center of the NEMA Motor mounts for Z movement on each side of the frame. Use the L brackets, ¼-20 inch screws, and standard T nuts to attach these pieces to the frame base.

2. Attaching the Last Piece of Aluminum 2020 Stock

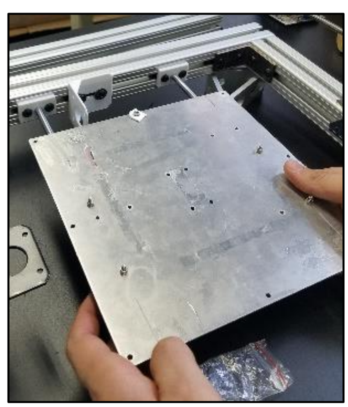
The third piece of aluminum 2020 stock allows for the power supply and Arduino board to be mounted in between the two pieces of stock.



1. Attach the third piece of aluminum 2020 in line with either of the other two pieces approximately 5.5 inches apart from their center slots. Attach using L brackets, ¼-20 inch screws, and standard T nuts.

3. Installing the HeatBed

The smooth rods should fit snugly into the smooth rod holders and the heatbed sit in the center of the frame base.

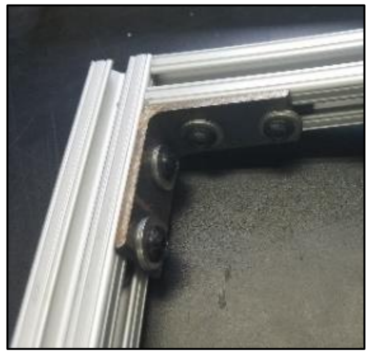


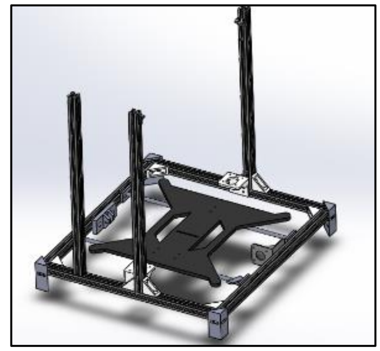
1. Press the same end of the two smooth rods into one set of the smooth rod holders.
2. Press the other end of the two smooth rods into the other set of the smooth rod holders. The heatbed should be suspended roughly two inches off the ground and should be able to slide back and forth smoothly.

4. Connecting the Frame Base

Prior to this step the frame base was still in pieces. Once it is all attached the frame base should form a square.

1. Attach the 4 pieces of 8020 stock at the corners in order to make the frame base into a square. Each piece should be connected at the corners using L brackets, ¼-20 screws, and standard T nuts.

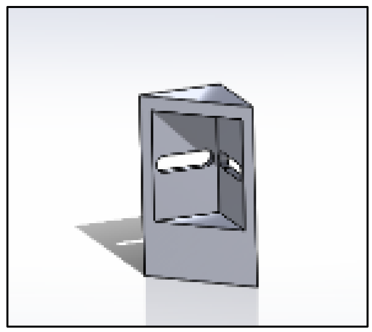




5. Attaching the Feet

The 3D printed feet of the printer elevate it off the ground and ensure that it sits level on whatever surface it is used on. They also serve to minimize vibration while printing for better quality prints.

1. Attach the 4 3D printed feet to each of the corners of the frame base. Use one ¼-20 screw and T nut for each foot.



Chapter 5: Y & Z NEMA Motors Installation

Required Parts

3x NEMA 17 Motors

2x 5x8mm Aluminum Flexible Shaft Coupler

2x GT-2 Teeth Timing Pulley

12x M3 Screw

12x M3 Nut

2-meter-Long GT-2 Timing Belt

24x ¼-20 Inch x 3/4 Screw with Standard T Nut

Required Tools

¼-20-Inch Hex Key

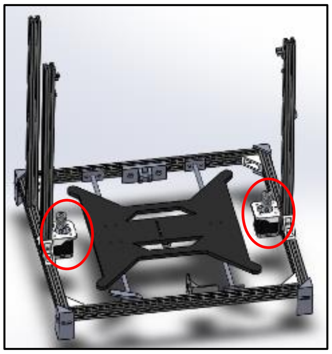
Scissors

5 NEMA 17 Motors are used on this 3D printer to drive the heatbed back and forth, as well as to move the extruder up and down. The two NEMA motors that are mounted adjacent to the XZ frame turn the threaded screw to move the extruder up and down. The rest of the NEMA motors rely on a pulley system using belts that loop around the gear like head that attaches to the NEMA motors and loop around smooth pullies on the opposite side. This includes the NEMA motor mounted offset from the center of the heatbed that moves it back and forth in the Y direction and the NEMA motor mounted on the XZ carriage that moves the Extruder back and forth in the X direction.

Steps

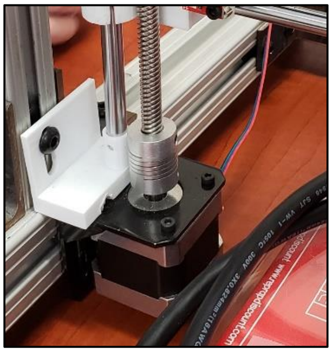
1. Attaching the Z Movement NEMA Motors

The Z Movement NEMA Motors are responsible for moving the extruder up and down.



1. Attach one of the Z NEMA motors to one of the two Z NEMA motor mounts on either side of the heatbed. Use M3 screws.
2. Attach the second Z NEMA motor to the remaining Z motor mount on the opposite side of the heatbed. Use M3 screws.

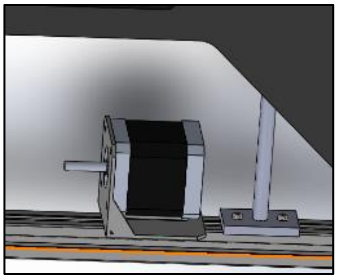
2. Attaching the NEMA Motor Couplers



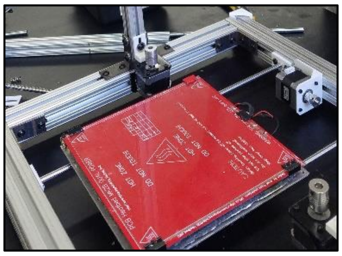
1. The coupler serves as the holder for the threaded lead screw that the NEMA motors turns. This screw is responsible for moving the 3D printed XZ carriages up and down.
2. Push the one of the couplers onto the tip of one of the Z NEMA motors. The coupler should fit snuggly.
3. Repeat this step for the remaining Z NEMA Motor.

3. Attaching the Y Movement NEMA Motor

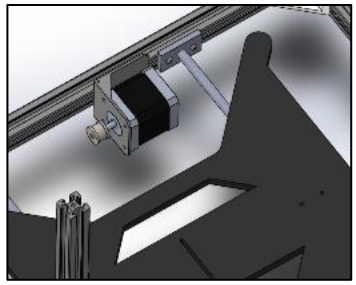
This NEMA motor is responsible for moving the heatbed back and forth in the Y direction. Instead of a coupler, a GT2 pulley with teeth is pressed on the end of the NEMA motor, for the belt to be looped around.



1. Attach the Y NEMA motor to the mount offset from the center of the heatbed. Use M3 screws.



4. Attaching GT2 Teeth Timing Pulley



The GT2 teeth timing pulley fits on the end of the Y movement NEMA motor. The teeth allow the timing belt to loop around it and prevent slipping.

1. Press the GT2 teeth pulley on to the top of the Y direction NEMA motor.

5. Attaching GT2 Y Movement Timing Belt

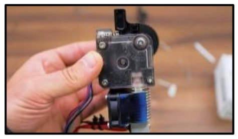
The GT2 Timing Belt loops around the GT2 teeth pulley at the end of the Y NEMA motor, around the smooth pulley on the opposite side of the heatbed and attaches to the belt holder on the bottom of the heatbed.

1. Cut a foot-length piece from the 2-meter timing belt using scissors.
2. Loop the belt around the smooth pulley and the GT2 teeth pulley, fastening it to the belt holder underneath the heatbed so the teeth on the belt catch the teeth of the belt holder.

Chapter 6: XYZ Movement Installation

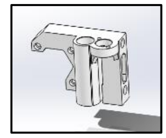
Required Parts

2x NEMA 17 Motors



2x E3D V6 Titan Extruder Kit

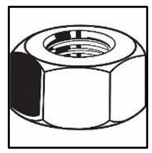
8x M3 Screws



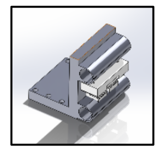
3D Printed Z Movement Bracket Left Side

8x M3 Nut

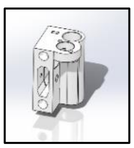
LM8UU Bearings



M8 Nuts



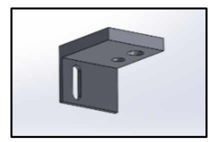
3D Printer Extruder Carriage



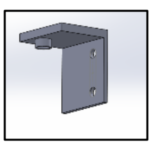
3D Printed Z Movement Bracket Right Side

2x Smooth Rods

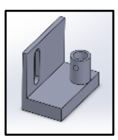
3D printed Belt Holder



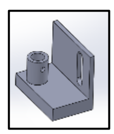
Top Smooth Rod Holders Left Side



Top Smooth Rod Holders Right Side



Bottom Smooth Rod Holder Left Side

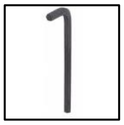
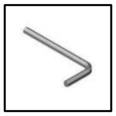


Bottom Smooth Rod Holder Right Side

4x ¼-20 Inch Screw with Standard T Nut

2x Threaded Rods with Flange

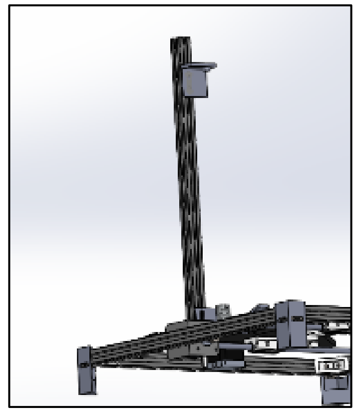
Required Tools

		
¼-20-Inch Hex Key	2.5mm Hex Key	Pozidriv Screw Driver
		
M8 Hex Key	M3 Hex Key	Epoxy

The YZ and X carriages hold the smooth and threaded rods in place, as well as the pulleys that much of the movement of the machine relies on. The extruder mounts to the X carriage which holds the smooth rods and pulley in place that allow the extruder to move back and forth. The carriages are all 3D printed so it is ideal to use ABS and a high-quality printer in order to ensure strength and lack of warping in the parts. If any of the carriages are warped, then the bearings that go inside of the carriages for smooth rods may not fit properly and hinder the mobility of the machine. The extruder itself is what lays down heated plastic material on to the heatbed layer by layer to create 3D objects. The extruder is mounted to a 3D printed carriage which is driven back and forth on smooth rods by the NEMA motors and pulleys. The extruder is made up of a heat sink, heating block, brass nozzle extruder, a fan, and a thermistor. The heating block heats up the plastic before extrusion and the heat sink above it prevents heat from traveling up the extruder and prematurely melting the filament.

Steps

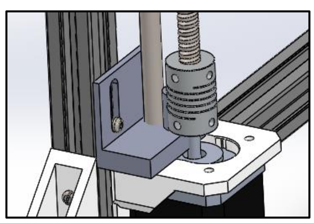
1. Attaching Top Smooth Rod Holders



The top smooth rod holders hold the smooth rods that the XZ carriages move up and down on in the Z direction.

1. Attach one of the 3D printed top smooth rod holders two inches from the top of one of the sides of the XZ frame. Use ¼-20 screws and standard T nuts.
2. Attach the second top smooth rod holder to the other side of the XZ frame. Use ¼-20 inch screws and standard T nuts.

2. Attaching Bottom Smooth Rod Holders

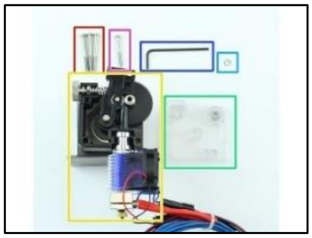


The bottom smooth rod holders hold the smooth rods that the XZ carriages move up and down on in the Z direction.

1. Attach one of the 3D printed bottom smooth rod holders two inches from the top of one of the sides of the XZ frame. Use ¼-20 screws and standard T nuts.
2. Attach the second bottom smooth rod holder to the other side of the XZ frame. Use ¼-20 inch screws and standard T nuts.

3. Assembling E3D V6 Titan Extruder Kit

The E3D V6 Titan Extruder V6 Kit holds the heat sink and extruder itself and provides a mode of feeding filament into the extruder itself.

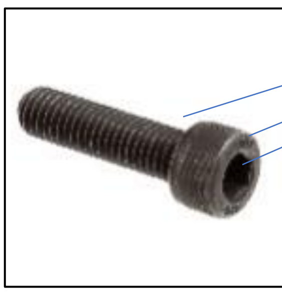


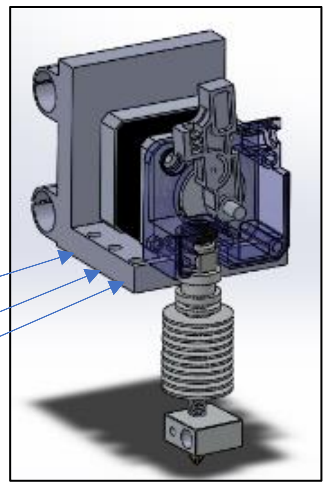
e3d-online.dozuki.com/Guide/1.75mm+Direct+Titan+Assembly/19?lang=en

1. Follow the guide at this link for manufacturer provided instructions on how to assemble the kit.

4. Attaching the E3D V6 Titan Extruder Kit to the 3D Printed Extruder Carriage

The 3D printed extruder carriage holds the E3D V6 Titan Extruder Kit and has holders for LM8UU bearings on the back side.





1. Attach the E3D V6 Titan Extruder Kit to the 3D printed extruder carriage using M3 screws and nuts.

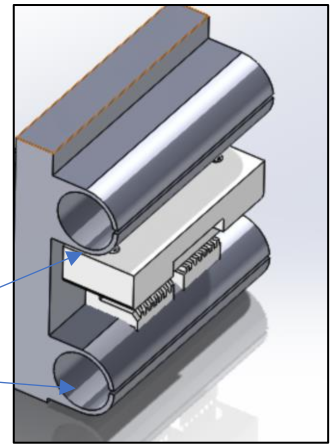
5. Attaching the Extruder Carriage Belt Holder

The belt holder on the back of the extruder carriage is responsible for holding the GT2 belt that controls the X direction movement of the extruder.

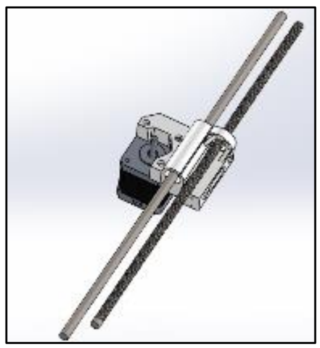
1. Insert LM8UU bearings into the back of the carriage.

Note: If the bearings fall out or move inside the carriage, glue can be used on the bearings to keep them in place.

2. Once the bearings are in place the belt holder can be attached to the back of the carriage using epoxy.



6. Attaching the Left Z Movement Bracket



The Left Z Movement bracket houses the bearing, smooth rod, threaded lead screw, and X NEMA motor.

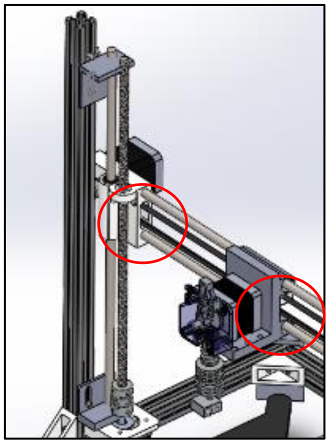
1. Insert one LM8UU bearing into the left Z movement bracket.
2. Attach one of the NEMA motors to the outer portion of the bracket using M3 screws and nuts.
3. Insert one smooth rod through the bearing.
4. Attach the threaded rod using the threaded rod, flange, and M3 screws and nuts.

7. Inserting the Smooth and Threaded Rods

The smooth and threaded rods move the left Z bracket up and down. They also keep the bracket parallel with the XZ frame.

1. Once the left Z movement bracket is assembled, the smooth rod should be inserted into the smooth rod holders and the threaded rod should be inserted into the NEMA Motor Coupler.

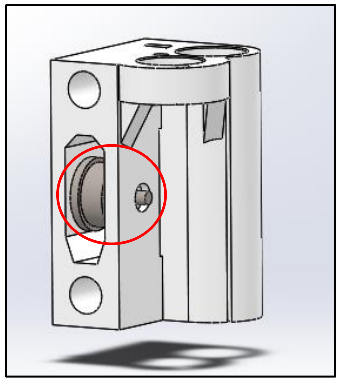
8. Attaching X Movement Smooth Rods

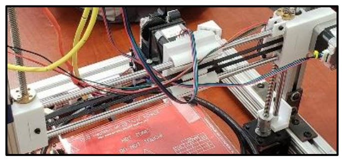


Two smooth rods should be inserted horizontally in the back of the 3D printed extruder carriage. Those smooth rods should then be slid into the left Z movement bracket.

1. Insert the first smooth rod into the top bearing on the extruder carriage and the top hole in the left Z movement bracket.
2. Insert the second smooth rod into the bottom bearing on the extruder carriage and the bottom hole in the left Z movement bracket.

9. Attaching the Right Z Movement Bracket



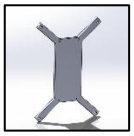


Repeat steps 1-7 on the opposite side of the machine.

1. Insert the smooth pulley for the X movement into the right Z movement bracket using an M3 screw and nut.
2. Loop the timing belt around the smooth pulley and the GT2 teeth pulley on the NEMA motor in the left Z movement bracket. Fasten it to the belt holder on the back of the extruder carriage, similarly to the heatbed.

Chapter 7: Power Supply and Arduino Board Installation

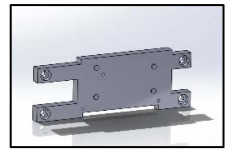
Required Parts



3D Printed Power Supply Mount

12 V Power Cord

8x ¼-20 Inch Screws and Standard T Nut



3D Printed Arduino Board Mount

ACER Racing Superworm Silicone Wire 14 Gauge 10' Copper Wire Very Flexible 14 AWG 400 strands

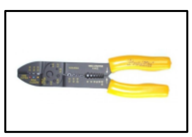
RAMPS 1.4

Arduino Mega 2560

12 Volt Power Supply

Required Tools

¼-20-inch Hex Key



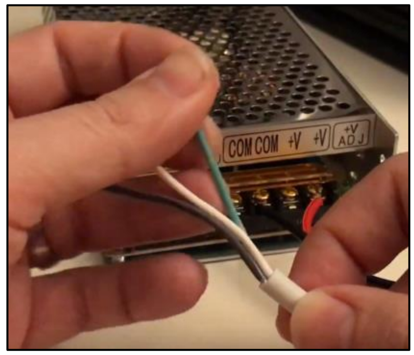
Wire Cutters

Cross Point Screw Driver

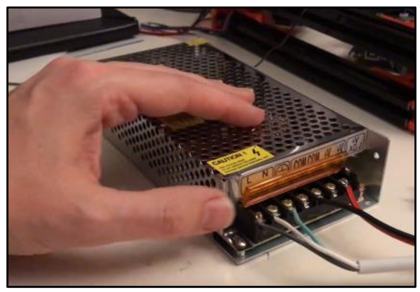
The power supply is 12 volt and supplies energy to the Arduino Board, NEMA Motors, heatbed, and extruder. This power supply is mounted to the one piece of the YZ frame and an additional vertical piece of aluminum 2020 installed adjacent to it. The mount is almost an "x" shape between the two pieces. In order to get power to the power supply, an average 12 volt power cord, should be stripped attached and the individual hot, neutral, and ground wires should be connected to their marked corresponding inputs in the power supply.

Steps

1. Connecting the Power Cord to the Power Supply



A normal 12 V power cord will be cut, stripped, and wrapped around the screws of the power supply. The male end will be plugged directly into the wall to provide power to the power supply.



1. Cut the female side of the power cord so the male side can still be plugged in.
2. On the cut side strip the three wires using the wire stripper tool. There should be three exposed wires: green, black, and white.
3. The black wire should go to the screw marked with the “L”.
4. The white wire goes to the Neutral screw marked “N” in the middle. and
5. The green ground wire goes to the “+” symbol.
6. Loosened each screw with the cross-point screw driver.
7. Wrap the copper threads of each wire as tightly as possible around the base of the screw.
8. Re-tighten the screw.

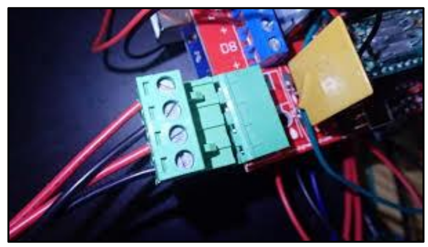
2. Connecting the Power Supply to the RAMPS 1.4 Board

Using the 14 gauge wire, the power supply will be connected to the RAMPS 1.4 board. This will supply the RAMPS 1.4 board with power and will allow for different components of the printer such as motors and limit switches to be connected.

1. Connect two of the black ends of 14-gauge wire to the two adjacent COM ports on the power supply.

   Note: The wires should be attached to the power supply by loosening and tightening the screws just as in Step 1.

2. Connect two of the red ends of the 14-gauge wire to the two adjacent +V ports on the power supply.
3. Connect these wires to the port on the RAMPS 1.4 board in order from top to bottom of red, black, red, black.



3. Mounting the Power Supply

Using the 3D printed mount, mount the power supply in between the adjacent pieces of aluminum 2020 stock.

1. Attach the power supply to the 3D printed mount using M3 screws nuts.
2. Once the Power Supply is attached to the mount, use ¼-20 screws and standard T nuts in the corner holes of the 3D printed mount to attach the power supply in between the two pieces of vertical aluminum 2020 stock.

4. Mounting the Arduino and RAMPS 1.4 Boards

Using the 3D printed mount, mount the Arduino and RAMPS 1.4 Board in between the adjacent pieces of aluminum 2020 stock, directly above the power supply.

1. Attach the Arduino Board and RAMPS 1.4 to the 3D printed Arduino Board mount using M3 screws and nuts.
2. Attach the mount directly above the power supply using ¼-20 screws and standard T nuts in the corner holes of mount.

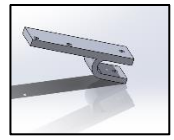
Chapter 8: Crossbar and Limit Switch Assembly

Required Parts

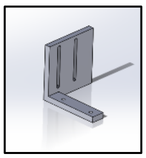
2x L Brackets

1x Aluminum 2020 Stock

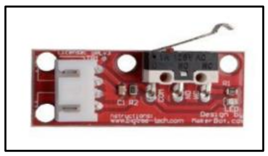
2x ¼-20 Inch Screws and Standard T Nut



3x 3D Printed X/Y Movement Limit Switch Mount



3D Printed Z Movement Limit switch Mount



3x Limit Switch

12x M3 Screws

Required Tools

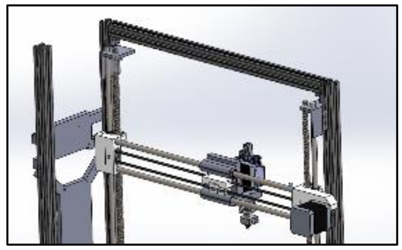
¼-20 Inch Hex Key

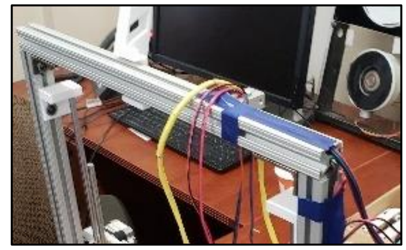
M3 Hex Key

The main purpose of the cross bar is to ensure that the two pieces of the YZ frame do not bow inward due to resulting forces of the machine running. The cross bar attaches across the top of the two pieces of the YZ frame. The cross bar is also aluminum 2020 stock and allows for a 3D printed filament spool holder to be attached. The purpose of the limit switch is to alert the printer to stop once the extruder or heatbed runs into it in either x, y, or z direction.

Steps

1. Attaching the Cross Bar

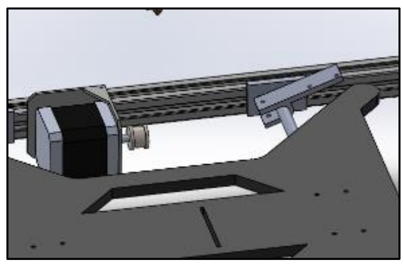




The aluminum 2020 cross bar provides structure to the rest of the frame and ensures that the two pieces of stock on the XZ frame are parallel.

1. Attach an aluminum 2020 piece of stock to the top of the two vertical aluminum 2020 pieces of stock. Use M8 Screws, L brackets, and T nuts.

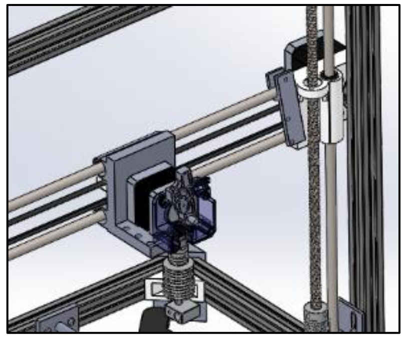
2. Attaching the Y Limit Switch

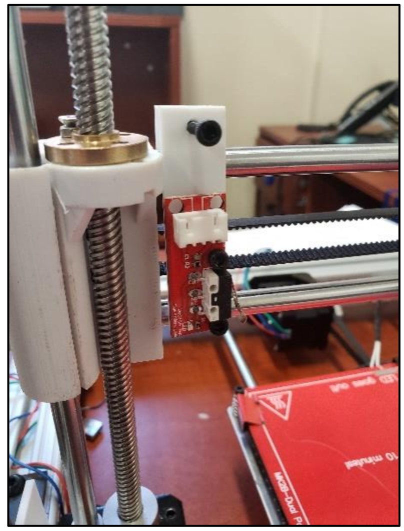


The Y limit switch prevents the heatbed from running into the NEMA motor or frame. Once the heatbed touches the limit switch it stops and returns to its original position.

1. Attach one of the three limit switches to the Y limit switch mount. Use M3 Screws and nuts.
2. Attach the limit switch and mount to the smooth rod closest to the tip of the Y NEMA motor. Use an M3 screw and nut.

3. Attaching the X Limit Switch

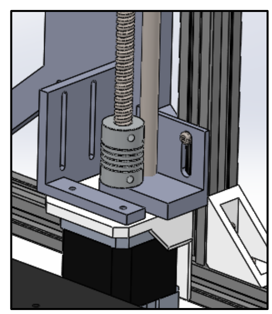




The X limit switch determines the parameters the extruder can move in the X direction and prevents it from crashing into the carriages.

1. Attach one of the limit switches to an limit switch mount using M3 screws and nuts.
2. Attach the limit switch and mount to the upper smooth rod using an M3 screw and nut.

4. Attaching the Z Limit Switch

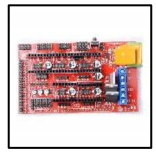


The Z limit switch determines the parameters the extruder can move in the Z direction and prevents the nozzle from crashing into the heatbed.

1. First attach the limit switch to the Z limit switch mount using two M3 screws and nuts through the two slots in the mount.
2. Attach the mount on top of the NEMA motor using the NEMA motor mount screws that are already there.

Chapter 9: Arduino and RAMPS 1.4 Boards Wiring

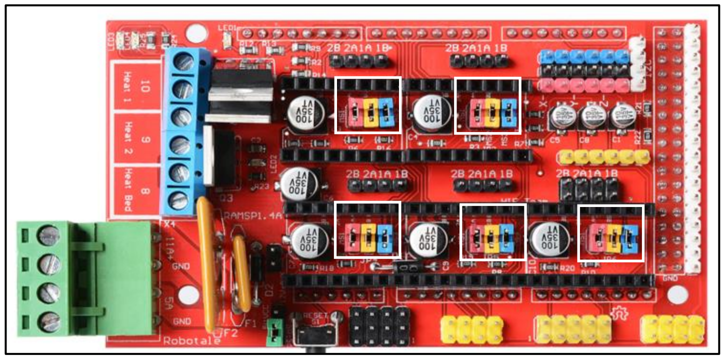
Required Parts

 5x UEETEK Stepper Motor Cables	 3x Limit switch Wires	 Arduino Mega 2560	 RAMPS 1.4 Board
 5x Stepper Driver	 LCD Smart Display Controller		

The Arduino board is the motherboard of the printer and controls the movement of the NEMA motors, the thermistors, and the extruder fan. However, the cables from all of these elements do not plug directly into the Arduino board itself. They plug into a RAMPS 1.4 board that is just a board that connects to the Arduino board that offers more inputs and can receive signals from the code uploaded to the Arduino board. The RAMPS 1.4 board also has ports that connect directly to the power supply, and in turn supplies power to the motors and thermistors.

Steps

1. Installing the Stepper Drivers

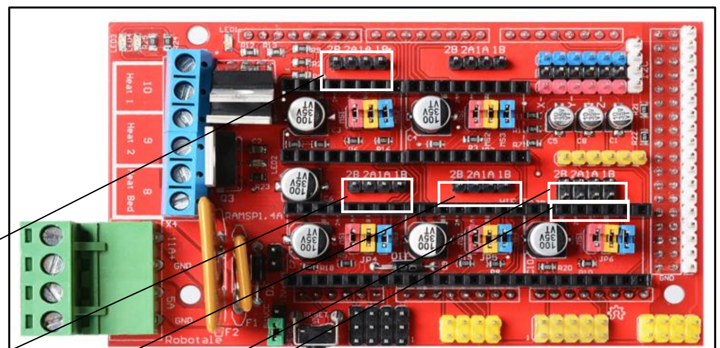


The stepper drivers control the coils in the stepper motors, causing them to trigger and rotate the motor precisely.

1. Install the five stepper drivers to their corresponding sets of pins.

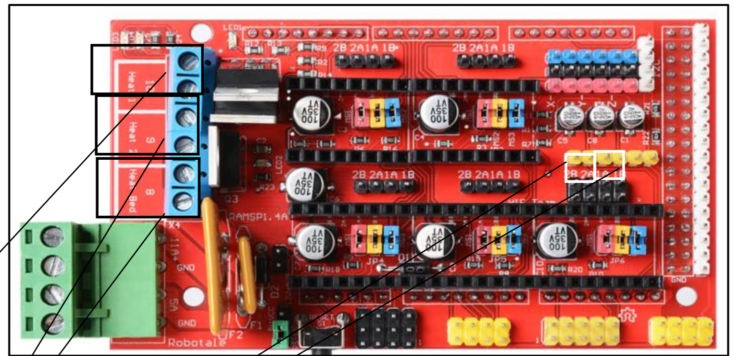
2. Plugging in the NEMA Motors

The X, Y, Z, and Extruder NEMA motors should be plugged in to their corresponding pins on the RAMPS 1.4 board. The Z motors should be plugged into the same box, one on top of the other. The black wires should also always be the furthest to the right.



1. Plug in the extruder NEMA motor to the top left set of four pins.
2. Plug in the X NEMA motor to the bottom left set of four pins.
3. Plug in the Y motor to the bottom middle set of four pins.
4. Plug the Z motors, one on top of the other, in the bottom right sets of four pins.

3. Plugging in the Heat Components

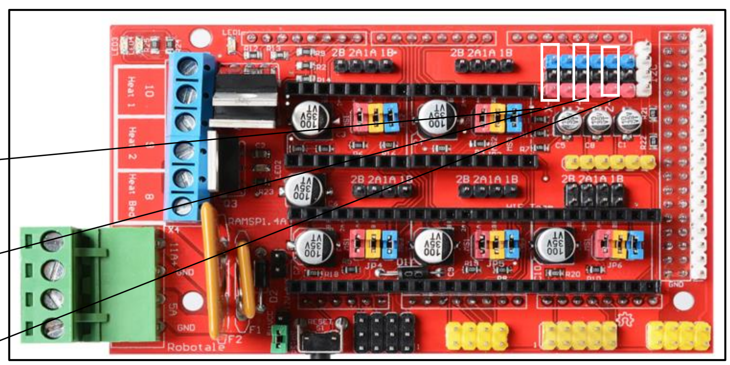


The heating components provide heat for the extruder to melt the filament for printing, provide a warm surface on the heatbed so the prints do not stick, and the fan prevents the extruder from overheating.

1. Plug in the extruder heater wires.
2. Plug in the extruder fan included in the E3D V6 Titan kit.
3. Plug in the heatbed wires.
4. Plug in the thermistors.

4. Plugging in the Limit Switches

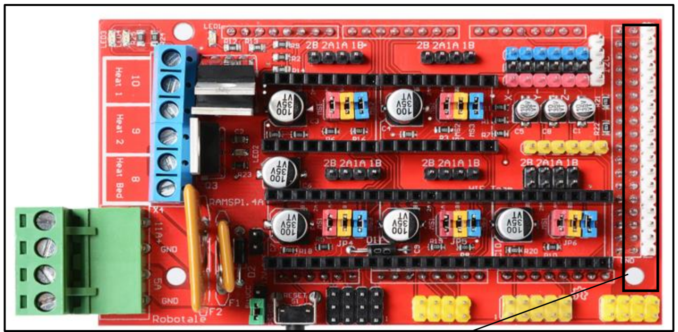
Since only three limit switches are used on this 3D printer only the X-min, Y-min, and Z minimum pins are used.



1. Connect the x direction limit switch to the furthest left set of pins.
2. Connect the y direction limit switch to the middle set of limit switches.
3. Connect the z direction limit switch to the right most set of pins.

   Note: Ensure that the limit switches wires are connected in order green, black, red from top to bottom.

5. Plugging in the LCD Screen



The LCD screen is used to manually control the 3D printer. It can jog the extruder and heatbed in the X, Y, Z directions as well as control the temperature of the extruder and heatbed. The LCD screen is optional since the printer itself will be operated using Pronterface software, which will be discussed further in the next chapter.

1. Connect the LCD screen to the long vertical set of pins on the far-right side of the board.

Chapter 10: Marlin Firmware and Pronterface Download

Required Parts

Arduino Mega 2560

USB Standard A-B Cable

Laptop or Desktop Computer with Internet Access

Marlin Firmware drives most 3D printers today, commercial and do-it-yourself. Marlin can be opened on multiple platforms, however, since this printer runs on an Arduino Mega 2560, Arduino is the platform that is used to open the Marlin code and configure the printer settings. Pronterface is a 3D printer host software, which allows the user to control their printer, without the use of an LCD screen or other manually installed controls. Pronterface allows for manual movement in the X, Y, and Z directions and can also control elements such as the temperature of the heatbed. G code can also be uploaded to Pronterface and be used to print parts easily.

Steps

1. Connecting the Arduino Board to the Computer

Once all the wiring is done, a computer can be connected to the Arduino board using the USB port and a USB A-B cord.

1. Connect the Arduino board to the computer using the USB A-B cord. The wider end should plug into the computer.

2. Downloading the Arduino App

The Arduino app allows for the Marlin code to be opened and modified based on your desired settings for the printer.

1. Download the app using this link:

   www.arduino.cc/en/Main/Software

3. Downloading the Marlin Code

Marlin in an open source firmware that controls the 3D printers, stepper drivers, heaters, sensors, extruder, and LCD display.

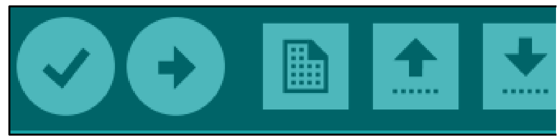
1. Download the Marlin code using this link:

   marlinfw.org/meta/download/

2. Once the file is downloaded navigate to its download location and open Marlin 1.1-x > Marlin > Marlin that should be an INO file. This will open the Marlin firmware in the Arduino platform.

4. Altering the Marlin Code

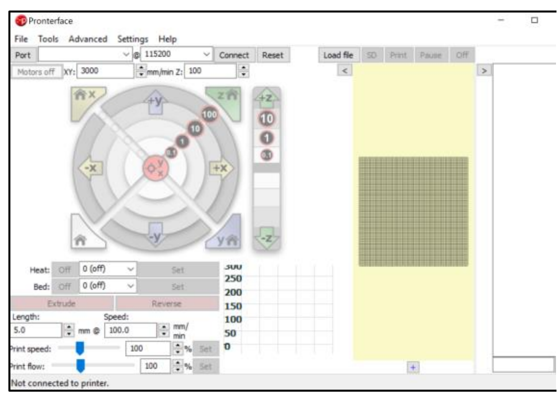
Most of the 3D printer settings can be changed in the Configuration.h tab in the arduino platform. Once you chosen your desired settings, you can compile and upload the code to the Arduino board.



1. In order to compile the code and ensure that there are no errors, click the check mark located in the upper right portion of the window.
2. Once the code has compiled without any errors, click the arrow pointing to the right to upload the code to the Arduino board.

5. Pronterface

Pronterface is a free software that allows users to manually control their 3D printer from their laptops. They can jog the heatbed and extruder in the X, Y, Z directions and alter the temperature of the extruder or heatbed.



1. Use this link to download the latest version of Pronterface for either Mac or Windows:

   kliment.kapsi.fi/printrun/

2. To Upload G-code to Pronterface use the "Load File" tab in the upper right-hand corner of the Pronterface window. You are now ready to print.

Appendix B. Bill of Materials

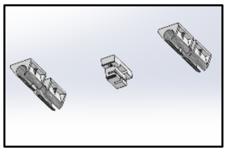
Appendix B. is the Bill of Materials for the 3D printer discussed in this manual. The bill of materials includes the name, quantity, and price of every part required to build the 3D printer. The Google Site also has the bill of materials along with sources for each part.

Item	Quantity	Price
6 x Nema 17 Stepper motor 40Ncm	1	48.99
6 x Stepper Motor Cables	1	10.49
Teflon (PTFE) Tube (5 ft 2mm ID 4mm OD)	2	11.98
2 x 623ZZ Bearing	1	5.85
3 x Limit switches	1	5.99
E3D Hotend module	1	11.11
240watt Power Supply w/ power cable	1	19.99
MK8 Extruder module	1	8.03
6mm fitting	1	15.7
PLA Filament	1	16.99
2 x 5mmx8mm Couplers	8	14.88
2 x GT2 Timing Belt (2m)	2	27.98
2 x Lead Screw + Flange Nut	2	21.98
6 x 8mm Smooth Rods	1	27.41
Smooth Rod Holder	1	10.99
Stepper Motor Mount	3	24.87
8 x SC8UU Bearings(Replacement for LM8UU Bearings)	2	19.76
8 x Angle Brackets (small)	1	7.99
8 x Angle Brackets (large)	1	9.99
10 x M3 Screws (long)	2	19.78
50 x M3 Nuts	1	1.86
2 x M8 Nuts	1	13.99
32 x M4 Screws	1	14.99
Acrylic Sheet 12x12	1	14.99
BIQU GT2 3mm Bore Aluminum Toothless Timing Belt Idler Pulley	1	$7.99
ACER Racing Superworm Silicone Wire 14 Gauge 10' Copper Wire Very Flexible 14 AWG 400 strands	1	$10.99
AmazonBasics Power Cord - 6-Foot, Black	1	$6.99
Aluminum 8020 stock	2 (48" length)	$36.43

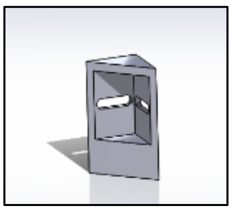
Stand Tools 20 Series, 20 mm x 20 mm T-Slot Aluminum Extrusion x 100 mm Pack of 4	1	$4.89
PZRT 2020 Series 50-Pack M4 T-Nuts,Carbon Steel Nickel-plated Half Round Roll In Sliding T Slot Nut 6mm Slot	1	$8.99
BIQU Aluminum MK3 12V Heatbed Platform 220x220x3mm PCB Hot Plate with Cable Line for Reprap 3D Printer	1	$14.99
OSOYOO 3D Printer Kit with RAMPS 1.4 Controller Mega 2560 board	1	$36.99
5pcs A4988 Stepper Motor Driver with Heatsink	1	Included in OSOYOO kit price
LCD 12864 Graphic Smart Display Controller with Adapter For Arduino RepRap	1	Included in OSOYOO kit price
Neodymium MQP B+ Powder	1 kg	$126.00
Nylon 12	92 ci	198
10pcs Stepper Motor Cable Wires	1	$10.99
580pcs Heat Shrink Tubes	1	$7.69
A4988 Stepper StepStick Driver Module	1	$8.99
Mechanical Limit switch Limit Switch (6 count)	1	$9.99
Colored Electrical Tape (12 pack)	1	$12.99
600pcs Colored Zip Ties Nylon	1	$8.99
TOTAL		743.93

Appendix C. 3D Printed Parts

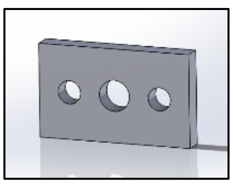
Appendix B. shows a picture and the name of every 3D printed part that will be needed to build the 3D printer discussed in this manual. All of the SolidWorks files for each of these parts are listed under the SolidWorks file page on the Google Site. It is assumed that you will be familiar with SolidWorks and have access to a 3D printer to print these parts.



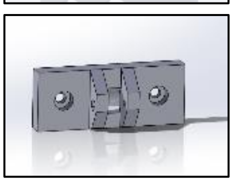
3D Printed Bearing Holders and Belt Holder



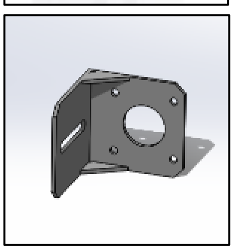
4x 3D Printed Frame Base Feet



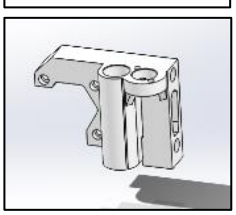
4x 3D printed smooth rod holders



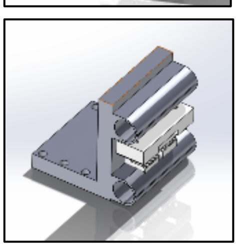
3D Printed Y Movement Pulley Mount



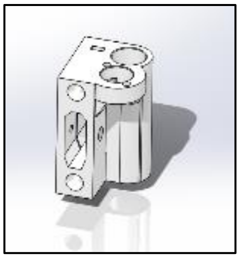
1x 3D Printed NEMA Motor Mount for Y Movement



3D Printed Z Movement Bracket Left Side

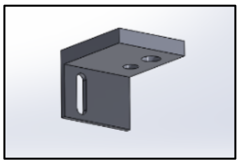


3D Printer Extruder Carriage

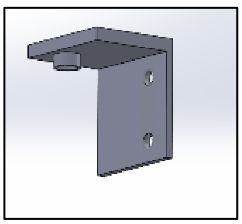


3D Printed Z Movement Bracket Right Side

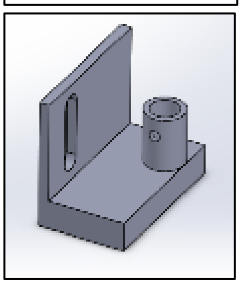
3D printed belt holder



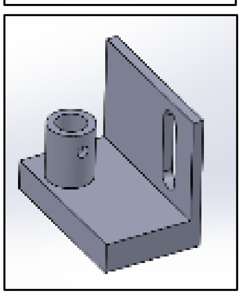
Top Smooth Rod Holders Left Side



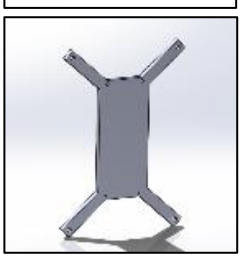
Top Smooth Rod Holders Right Side



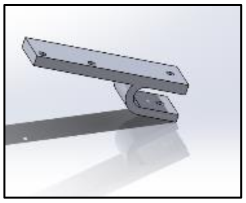
Bottom Smooth Rod Holder Left Side



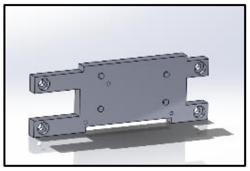
Bottom Smooth Rod Holder Right Side



3D Printed Power Supply Mount



3x 3D Printed Limit switch Mounts



3D Printed Arduino Board Mount

Appendix D. Focus Group Procedure

Research Questions:

- Was this manual helpful in explaining the selected tasks for building a 3D printer?
- Do users prefer to use manuals for large construction projects, or work through the project on their own?

Introduction Engagement Questions:

1. What is the last product you purchased that included a manual?
2. Did you use this manual?
3. Do you generally use generally use the manuals that come with products you purchase?

Interactive Tasks:

4. Using the provided parts, please attach the limit switch and limit switch mount to their correct position on the 3D printer. Please navigate to this specific section in the manual and follow the given instructions.
5. Please connect the already installed Y Motion NEMA Motor to its corresponding pins on the RAMPS 1.4 Board. Please navigate to this specific section in the manual and follow the given instructions.

Explorative Questions:

6. Would you have preferred more or less text in each step and why?
7. What about the visuals could have been improved?
8. Do you feel confident that you could build a 3D printer using this manual, based on the tasks you completed, and if not, what would you change?

Exit Questions:

9. Is there any other feedback would you would like to give on the manual?
10. Do you have any questions or concerns about the focus group?

Appendix E. Focus Group Responses

	Q1	Q2	Q3	Q6	Q7	Q8	Q9
Focus Group 1							
Person 1	Phone Screen	Yes	No	Less text in the opening.	More pictures showing what each part looks like in the required parts section and in the steps section.	For positioning the endstops it was helpful, but there should be more pictures for attaching the endstop.	Yes
Person 2	Toilet	Yes	Yes	Amount of text is fine.	Show in depth once how to put endstops together and then just say to refer back to that step for the next two endstops.	I kind of had an idea of where the endstops went although I probably could have figured it out without a manual. That was not true for connecting the Motor. I could not have done	Yes
Person 3	Bed Frame	Yes	Yes	Less text overall would be b	More and larger pictures would be good.	The biggest advantage of this manual is the chronological order. It is easy to put together pieces in a project like the out of order when you're trying to follow youtube videos or a	Yes
Focus Group 2							
Person 1	IKEA Shelf	Yes	Yes	The amount of text was fine, but the spacing seemed a little off.	Use a real picture instead of a drawing for the wiring.	have been able to wire the motors without the manual.	yes
Person 2	Car Radio	No	No	The amount of text seemed reasonable.	Larger pictures and arrows showing the order of assembly.	The manual was helpful but I think that videos would probably be	no
Person 3	Compass	No	Yes	The amount of text was fine.	More real pictures instead of screenshots.	I knew that the end stops were essentially limit switches, but the manual showed exactly where they attached, which	yes
Focus Group 3							
Person 1	Apple Watch	No	No	The steps could have been more clear. So maybe more text.	The wiring diagram does not look like the actual board, which is confusing.	organized and clear. The weak point was the pictures, but if that is addressed it seems pretty useful.	yes
Person 2	Samsung Gear	Yes	Yes	Less text is definitely better.	There needs to be more pictures in the endstop section.	It's hard to say from only these two chapters, but I was able to complete both of the tasks so I would assume the rest of the	no
Person 3	Bluetooth Speak	No	No	The introduction paragraph wasn't really clear so maybe either improve that or get rid of it	It wasn't clear that the end stop needed to be attached to the mount before being attached to the printer. You should add pictures	The tasks were pretty easy to complete using the manual, I would say it's useful.	yes

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