



JMS-1704: Multihead 3D Printer

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Abstract

Since their development in the 1980's, 3D printers have become a staple within the rapid prototyping process. 3D printing, also known as additive manufacturing, is the process by which a product is built layer by layer using raw material rather than taking material away from a larger stock. The material can take many forms, including filament, pellets, and powders. There are limitations to current printers, however. Many commercial printers utilize a maximum print volume of about 8in x 8in x 8in, limiting the size of printable parts and forcing the pieces of a larger prototype to be constructed separately and then assembled. Production of similar parts is also a slow process with traditional single extruder printers, limiting your work to one part at a time. In addition, most commercial printers are limited to a single strand of filament per print, preventing parts from being able to print in multiple colors or materials.

This project developed a filament-based 3D printer that utilized a larger print space than commonly available printers on the market, is capable of operating multiple hotends simultaneously, and is able to fabricate printed parts that require two or more colors. Because of the scale of this project, the work to be done was divided amongst three groups: the Platform group that focused on the heated beds and printer structure, the Controls group that focused on the programming and electronics associated with the printer, and the Extruder group that focused on the hotends, carriages, and extruders themselves. This report documents the work done by the Extruder team.

In order to print similar parts simultaneously, we worked with the concept of three extruders operating at once and designed the hotend carriages, which are physically connected so that the motion of the primary head would translate to the two auxiliary heads. We then worked with the Controls group to run the software of each extruder in parallel with the others, allowing the hotends to work in tandem and produce multiple copies of the same part at once.

To allow the printer the ability to print parts in multiple colors without manually switching out the filament for each section of color, we utilized a Diamond Hotend. The Diamond Hotend has the unique feature of having three individual filament inputs, which allows prints to use more than a single color during printing without requiring a user to switch out the filaments themselves. This head also has the capability of mixing colors together in the nozzle and extruding a new color onto the bed. Working with the Controls group, we used a version of firmware that would allow color mixing. This allows the printer to extrude different percentages of yellow, magenta, and cyan filaments into the Diamond Hotend at the same time and melt them together, allowing the pigments to combine into a new color from the used filaments. From yellow, magenta, and cyan, we were able to create sixteen additional colors.

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1. Introduction

Traditionally, machining a product required the use of subtractive manufacturing. Subtractive manufacturing involves carving the product out of a solid block of material by removing the unwanted portions through use of a lathe, Computer Numeric Control (CNC) machine, or similar device. Products are molded by injecting the liquefied material into a form and allowing it to harden in the desired shape. In 1984, a new method of additive manufacturing was made possible (Ponsford & Glass, 2014). This alternative method involved building products layer-by-layer, adding material until the final shape was completed. Today, additive manufacturing, or 3D printing, has found widespread use in scientific fields from biomedical to aeronautical and almost every discipline in between.

3D printing has become a valuable resource for prototyping an idea. The ease of production through 3D printing has benefited hobbyists looking to develop a product in the comfort of their own home. However, current consumer 3D printers are limited in their printing capabilities. Typically, these printers are only capable of printing objects about 8in x 8in x 8in, or about the size of a half-gallon of ice cream. While some 3D printer designs are capable of producing products in multiple colors, this feature is not commonplace on commercial 3D printers and thus severely limits the creative applications of 3D printing. It is possible to adapt many 3D printers to a variety of materials, but the process of preparing the printer for a new material is tedious and may even increase the probability of damaging the print head. As a result, most commercial 3D printers are limited to printing one type of material.

The 3D printing industry has grown rapidly since the 1980s, but there is room for further developments in the capabilities of 3D printers, particularly for home use. Our team developed a large-scale 3D printer capable of instructing multiple print heads simultaneously. Additionally, this printer can accommodate multiple materials, and can print objects using a diverse pallet of colors, all without changing filament reels.

2. Background

3D printing is a method of additive manufacturing that produces three-dimensional objects from a computer model (Williams, 2015). Early 3D printers used light activation to slowly build one layer of a material on another until the desired object was produced. The first 3D printer of this style, known as stereolithography, was invented in 1984 and used UV light to activate and solidify a resin in layers, thereby building up a prototype (Williams, 2015). It took four years to develop a commercial stereolithography printer (History of 3D Printing).

Around the same time, another method of 3D printing using filaments of material to build up the layers was being developed. In 1989, the first Fused Filament Fabrication (FFF) printer was invented (Hughes, 2015). FFF printers using PolyLactic Acid (PLA) or Acrylonitrile-Butadiene Styrene (ABS) plastics are most common among the consumer market. PLA is a biodegradable plastic made from cornstarch or other raw materials. ABS is a durable, oil-based plastic commonly used in products that will need to stand up to continued use. Both

plastics offer different benefits and require different settings when being 3D printed (Grieser, 2016). While PLA and ABS are the most common filament choices, there is a wide variety of printing materials being used in several different methods of 3D printing throughout the industry. The following chapter will discuss the different printing methods and materials, as well as the key components of FFF printers.

2.1. Printing Methods

The materials used in additive manufacturing can take a variety of forms, including filaments, powders, and pellets. Each material form requires a different method of printing. FFF printers involve spools of filament fed through a heated extruder and deposited in layers on a flat bed surface. Powder 3D printers involve a print head extruding a liquid binding material into a powder base, solidifying the desired areas for each layer of printing. 3D printers using material in a pellet form require a hopper to store the pellets, which are then fed into the heated print head and extruded onto the bed surface layer by layer. The upcoming Figures 1-3 show examples of a filament, powder, and pellet 3D printer, respectively.



Figure 1: Example of a 3D printer that utilizes filament



Figure 2: Example of a 3D printer that utilizes powder

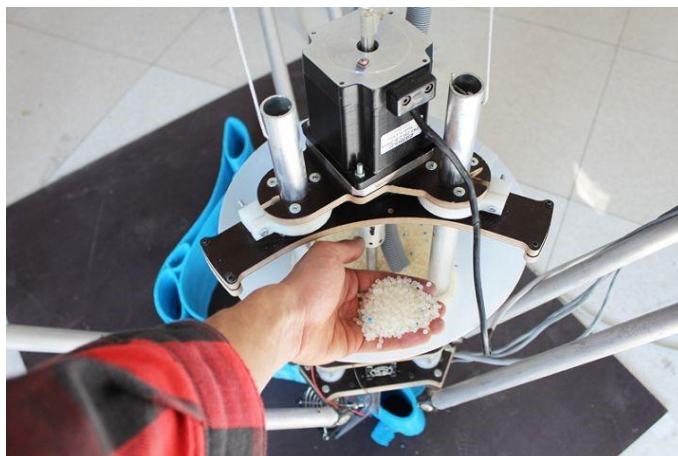


Figure 3: Example of a 3D printer that utilizes pellets

The most common method used by commercial 3D printers is FFF (Palermo, 2013). In this method, material is initially molded into plastic filaments or metal wires, usually of diameter 1.75 or 3.00mm. When ready to begin printing, the filament or wire is unwound from a coil through an extrusion nozzle. The material is then heated until molten and laid down on the print bed by the extruder, in a shape controlled via computer and 3D modeling software. As the material exits the extruder nozzle, it fuses to itself and hardens. This process is repeated, building the product up layer by layer, until the 3D model has been fully realized. (What is 3D Printing? 2016).

An alternative printing method uses small particles of powdered plastic, metal, ceramic, or glass. The powders are solidified into the desired shape using a high-powered laser or electron beam to melt and fuse the particles together. Between each fusion of layers, a roller or blade applies a new layer of powdered material (Powder Bed Fusion, 2016).

A third method, known as material jetting, applies material droplets to the print surface to be solidified and cured using a UV light. Again, the object is then built up layer by layer. As of now (Up until recently), material jetting is (was) the only 3D printing process that can (could) combine multiple materials in the same print job (Material Jetting, 2016).

2.2. Materials

The FFF method can utilize a large range of plastic and composite filaments. The two most commonly used filaments in desktop 3D printing models are PLA and ABS (Matterhackers, 2016). PLA is a biodegradable thermoplastic polyester that is commonly derived from renewable resources like cornstarch and sugar cane. It is odorless when printed and has low susceptibility to warp, meaning that a heated print bed is not required when printing PLA. When compared to ABS, PLA is harder, slower to wear, and easier to attain a flat part, but at the cost of being a more brittle plastic. ABS is less brittle and able to withstand higher impacts and temperatures. It

is, however, more susceptible to warping and thus requires a heated bed in order to avoid warping in finished products. A bed temperature range of 80-110° C is recommended.

Another material used in 3D printing is Nylon. Relative to other 3D extruded filament such as PLA and ABS, Nylon is incredibly strong, durable, and versatile. However, Nylon is also very susceptible to moisture, so careful drying techniques must be used during storage and immediately before use. Nylon requires a much higher extrusion temperature than PLA or ABS, averaging about 235-270° C. Successful Nylon prints also require heating the bed to between 60-80° C.

Similar to Nylon, Polycarbonate is highly resistant to impact and is very strong, which can be shown in its use in the construction of bulletproof glass. Also like Nylon, Polycarbonate requires high temperatures in order to be malleable, with an extruder head and print bed temperature of 270-310° C and 90-105° C respectively.

Support materials are crucial when extruding parts that utilize complex geometries as these prints will require physical support throughout the printing process. Polyvinyl Acetate (PVA) is a common support material used in the printing of ABS and PLA because it is water soluble, meaning that it will dissolve when exposed to water. High Impact Polystyrene (HIPS) functions similar to PVA, the only difference being that it requires a chemical solvent to breakdown and dissolve (Matterhackers, 2016). A more thorough analysis of print materials is included in Appendix A.

2.3. Printing Mechanisms

Two components vital in the operation of an FFF 3D printer are the extruder and the hotend. The extruder, shown in Figure 4, is responsible for driving the filament through the 3D printing system. A stepper motor activates gears, which in turn grip the filament and push it through the hotend and onto the print bed.

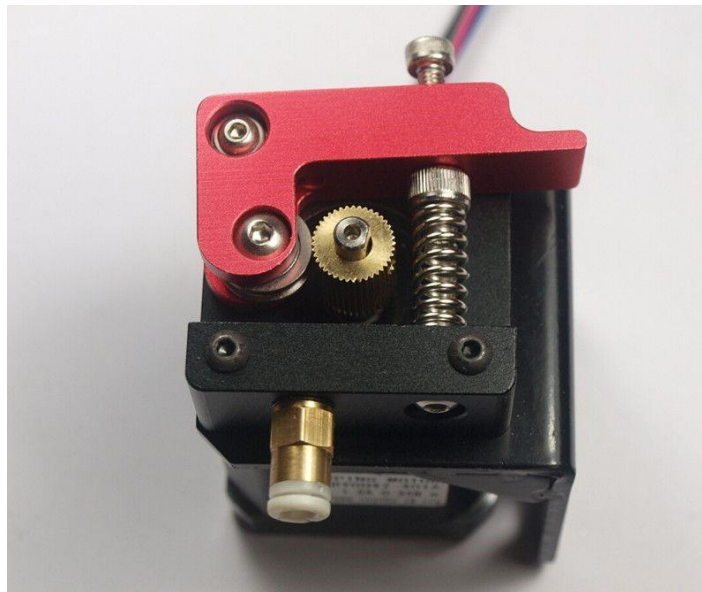


Figure 4: 3D printer extruder (AliExpress, 2016)

An FFF hotend is shown in Figure 5. This component is made up of a guiding tube for the filament, a heating element, and a brass nozzle. The extruder will drive the filament through the hotend where it will be heated until molten and then further extruded through the nozzle and onto the print bed. Once heated, the nozzle also serves to decrease the filament diameter from the initial 1.75 or 3.00mm to 0.2, 0.3, or 0.4mm, depending on the nozzle.



Figure 5: 3D printer hotend (Ooznest, 2017)

These critical components can be arranged in either a direct mount or Bowden mount on the 3D printer. In a direct mount system, the hotend is mounted directly to the extruder, as shown in Figure 6 with the Makerbot Replicator. Here, the hotend and extruder are combined in a single assembly.

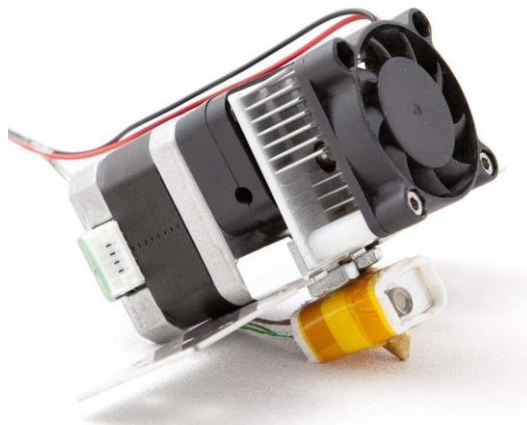


Figure 6: Direct drive setup used in the Makerbot (RoboSavvy)

Bowden mount systems separate the extruder from the hotend and use polytetrafluoroethylene (PTFE) tubing to guide the filament between the two assemblies, as

shown in Figure 7. With a Bowden mount, the heavier extruder can be mounted to the frame of the printer, reducing weight on the moving print heads when compared to the direct mount. However, the tubing leading from the filament reels to the print heads can bind or cause otherwise deform the material inside. Bowden style systems are used on printers such as the Makerbot Smart Extruder and RoVa3D Dual Extruder.

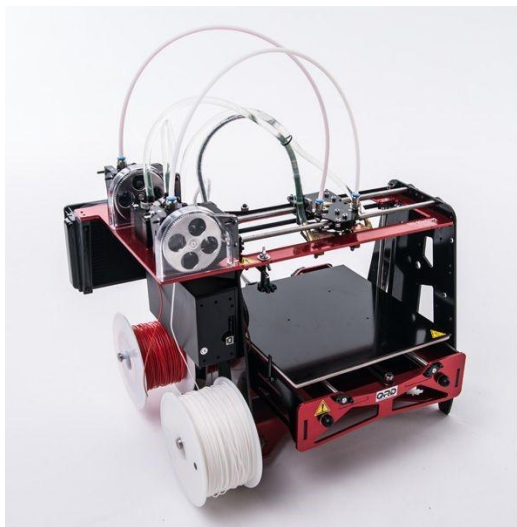


Figure 7: Rova3D Dual Extruder, which uses a Bowden style printer setup (ORD solutions)

2.3.1. Extruders

The extruder of a 3D printer is responsible for controlling the material feed into the hotend (see Figure 8). The most basic extruders work with a filament drive gear, stepper motor, and idler. The filament drive gear transfers the energy of the stepper motor and applies it to the filament, forcing the filament through the hotend where it is melted and deposited. The stepper motor is how the feed rate of the extruder is controlled, and is available in different sizes to account for different torque and power draw requirements. The stepper motor is able to control its degree of rotation, allowing for precise motor controls. The idler is commonly made from a bearing and serves to maintain pressure between the filament and the drive gear. The idler keeps the drive gear from slipping and helps to maintain constant material feeds (Landry, 2016).



Figure 8: Open extruder to show the filament and its interaction with the drive gear and idler (Unknown)

Direct extruder setups, as seen in Figure 6, are able to provide better responsiveness and easier flexible material compatibility when compared to Bowden extruders. They also require less torque to drive the filament into the hotend. However, the added mass to the moving components of the printer can result in slower speeds. In some cases the added weight can even cause the frame of the printer to wobble during operation or the nozzle to lose accuracy as it may overshoot where it should be positioned due to the added mass (Stevenson, 2015; Landry, 2016).

Bowden extruder setups, as seen in Figure 7, allow for less moving mass within the 3D printer, allowing for potentially faster and more accurate prints when compared to a direct drive configuration. The larger distance between the extruder and the hotend can cause the setup to be less responsive, but this can be accounted for in the setup of the printer. Bowden setups also require more torque to drive the filament due to the added friction between the PTFE tube and the filament; this can be overcome with extruders incorporating gear reductions or stepper motors with higher torque ratings. The added friction can also cause issues when printing flexible filaments (Stevenson, 2015; Landry, 2016).

Both Bowden and direct extruders have their inherent strengths and weaknesses, and the use of both is possible through correct printing settings and setup. Whether either is used for a particular printer depends on the requirements of the user and desired operation of the printer.

2.3.2. Hotends

The hotend of a 3D printer is responsible for melting and depositing material. The hotend assembly (see Figure 9) works by feeding the filament into a melt zone, where the filament is melted for deposition through the nozzle. Incoming material causes the previously melted filament to be expelled through the nozzle tip. The melt zone area is controlled through either cooling or insulating to keep the filament from melting prior to the melt zone. The melt zone is located within the heater block of the hotend. The heater block is responsible for holding the heating element and temperature sensor to maintain the necessary temperatures for print operations. The nozzle of the hotend is connected to the heater block, and acts as part of the melt

zone. The nozzle is responsible for melting the incoming filament and depositing the filament onto the work piece. The nozzle can be made in different sizes to account for different feed rates and print quality. Larger nozzles allow more material to be placed at once, but limit the surface quality of the finished piece.

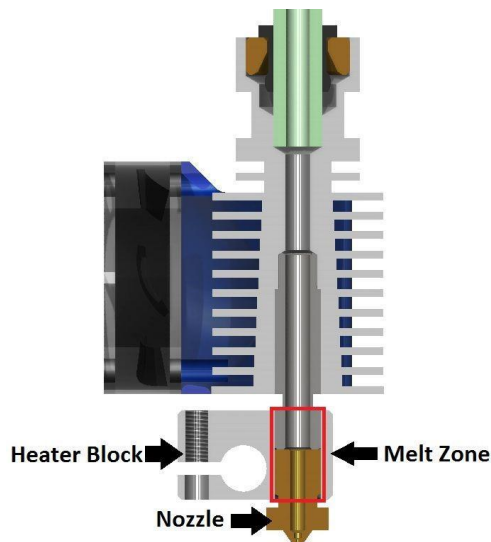


Figure 9: Cutaway of the E3D v6, with melt zone, heater block, and nozzle labeled (E3D-Online, 2014)

2.3.2.1. PEEK Hotends

PEEK hotends are generally the least expensive and most basic of the hotend designs (see Figure 10). They limit a printer to the use of filament materials with a melting temperature below 240°C - commonly ABS and PLA- because the PEEK portion of the hotend cannot withstand high enough temperatures to melt materials such as Nylon. Using the hotend above 240 °C causes the PEEK materials to breakdown as it exceeds their maximum operating temperatures (Landry, 2015).

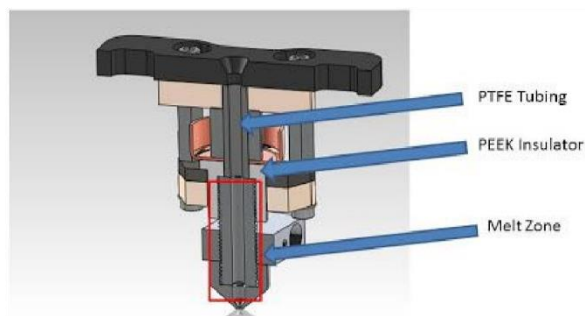


Figure 10: Cutaway of a PEEK hotend, note the PEEK in direct contact with melt zone and no active cooling (matterhackers, 2015)

2.3.2.2. All-Metal Hotends

All-metal hotends are more expensive than their PEEK-based counterparts are, but expand the printing options to include of printing with high-temperature filament, such as Nylon and Polycarbonate. As seen in Figure 11, they are constructed of only metal components within

the high temperature areas of the hotend. They also use active cooling, such as a fan blowing over a metal heatsink, to keep incoming filament from melting prior to the melt zone. All-metal designs also use a heat break to limit the rate of heat transfer between the heater block and the heatsink. Hotends such as the E3D v6 and the DyzEND-X allow for printing temperatures of up to 300°C and 500°C from the manufacture respectively (E3D-Online, 2014; Dyze Design).

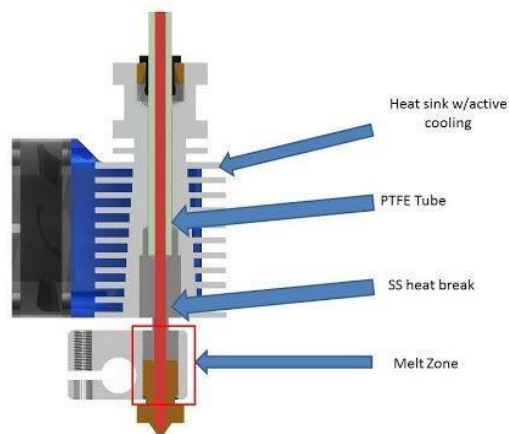


Figure 11: E3D v6 cutaway, note the active cooling and PTFE tube being away from the melt zone (matterhackers, 2015)

2.3.2.3. Multi-Material Hotends

Multi-material hotends allow for the use of multiple filaments with one melt zone and nozzle. By using only a single nozzle, the hotend is able to use multiple materials without the common issues of oozing and calibration, which can be compromising when two separate hotends are used (Klarmann, 2015). Oozing is the deposition of material from an unused hotend onto the work piece. This deposition can affect the finished quality of the piece and require additional finishing to remove the excess material (see Figure 12). With two nozzles, each must be set to the same z-height and with precise offsets in order to ensure that the head is colliding with neither the print bed nor the parts being printed. As coordinating between multiple heads can often be difficult, calibration issues are more likely to arise with multiple heads, and incorrect calibration can cause poor print quality or failure during the print procedure (see Figure 13).



Figure 12 (left): Oozing left on the surface of a finished print (Nick Lievendag, 2014)

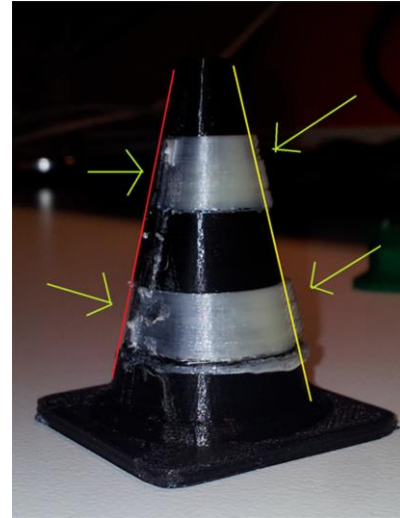


Figure 13 (right): Incorrect printer offsets caused the layers to print in the wrong location (Center for Educational Innovation and Technology, 2013)

Multi-material hotends such as the Diamond Hotend, as seen in Figure 14, can also provide the ability to mix different colors of the same filament. This feature means that the user can stock three basic filament colors, but allows the possibility to print in colors that would otherwise have to be stocked as separate filament (Klarmann, 2015).



Figure 14: Diamond Hotend, note 3 filament inlets meet at a single nozzle and heater block (RepRap.me)

Multi-material hotends do have drawbacks. One major drawback is the waste of material required when switching colors or materials (Klarmann, 2015). Filament is wasted because the hotend needs to flush the melt zone of the previously used color or material before beginning with the next color or material. Without first purging the previous filament, the next print layers would be made with a mixture of different colors or materials, causing unwanted appearance or even affecting print or material quality. As seen in Figure 15, a prime tower has to be used to flush the melt zone between filament changes.

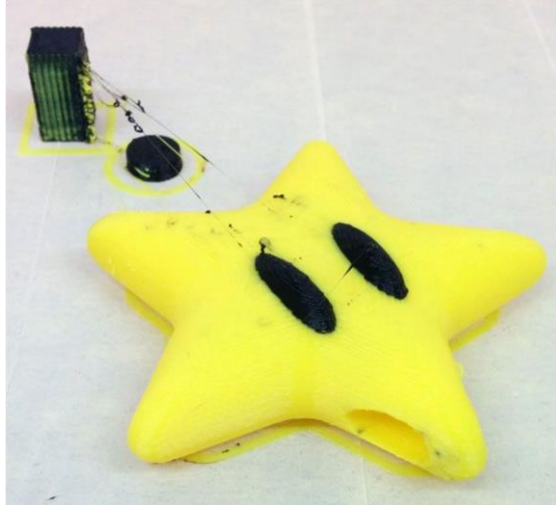


Figure 15: Prime tower and print (Nick Lievendag, 2014)

3. Design Selection

3.1. Hotends

Throughout the design stages multiple ideas had been presented, the pros and cons of three designs were listed. The different designs were then to be rated using a weighted decision matrix. Before comparing the individual designs, design goals were defined as follows:

1. Flexibility - Material processing, material selection, modes of operation
2. Cost - Overall cost of construction, cost of operation
3. Weight - Printer carriage weight
4. Maintenance - Ease of construction, maintaining printer, servicing, frequency of service
5. Space Efficiency - Ability to use maximum bed area

The weights for the design goals were then determined by weighing each design goal against the others, giving it a one if it was more important, a .5 if it was equally important, and a zero if it was less important. The final weights were then calculated and used as multipliers for the individual scores given to each design in a decision matrix. The individual scoring for each design was given based on a one-to-ten scale, with ten being the highest possible success in a given criteria. Scoring was determined by coming to a consensus as a group. With the decision matrix filled, final scores were calculated using the obtained weighting. The design, which received the highest score, is the Diamond Hotend and the custom X-into-1 hotend adapter. Ultimately, the Diamond Hotend was chosen due to its ability to mix colors and greater use flexibility outweighing the additional cost and weight associated with the design when compared to the X-into-1 hotend adapter.

	Flexibility	Cost	Weight	Maintenance	Space Efficiency	Total
Flexibility		1	0.5	1	1	3.5
Cost	0		0.5	1	0.5	2
Weight	0.5	0.5		0.5	0.5	2
Maintenance	0	0	0.5		0.5	1
Space Efficiency	0	0.5	0.5	0.5		1.5

Table 1: Hotend Design Goal Weighting

	Individual Hot End		Diamond Hot End		Custom Hot End Attachment	
Flexibility	7	25	8	28	5	18
Cost	4	8	5	10	7	14
Weight	3	6	5	10	7	14
Maintenance	5	5	5	5	6	6
Space Efficiency	4	6	7	11	8	12
		50		64		64

Table 2: Hotend Decision Matrix

3.2. Z-Axis

Two ideas for creating z-axis movement were introduced by the platform group, one to move the bed in the z-axis another to move the heads in the z-axis. The different designs were then to be rated using a weighted decision matrix to provide insight into the better of the two ideas. Before comparing the individual designs, design goals were defined as follows:

1. Flexibility - Ability to work w/ different hot-ends/extruder designs
2. Cost - Total cost of setup, cost of operation
3. Weight - Static/dynamic weights
4. Maintenance - Ease of construction, hot-end replacement, bed leveling
5. Performance - Accuracy, ease of motion, printing speeds

Just as with the hotend design goals, the weights for the design goals were then determined by weighing each design goal against the others. The design, which received the highest score, is the bed moving in the z-direction. This was due to the thoughts that it offered greater flexibility with a range of hotends and other tooling devices and that the bed would be the lighter of the assemblies. The decreased weight could allow for less power in the z-axis drivetrain, increased printing speeds, and greater accuracy.

	Flexibility	Cost	Weight	Maintenance	Performance	Total
Flexibility		1	1	0.5	0.5	3
Cost	0		0.5	0.5	0	1
Weight	0	0.5		0	0.5	1
Maintenance	0.5	0.5	1		0.5	2.5
Performance	0.5	1	0.5	0.5		2.5

Table 3: Z-Axis Goal Weighting

	Moving Head		Moving Bed	
Flexibility	4	12	8	24
Cost	4	4	6	6
Weight	4	4	7	7
Maintenance	5	12.5	6	15
Performance	4	10	7	17.5
		42.5		69.5

Table 4: Z-Axis Decision Matrix

4. Design Iterations

Once background research had been collected and we identified the print heads for our printer, we began designing the print carriages that would accommodate these print heads. In order to maximize functionality of our 3D printer, we opted to include a permanent, Diamond Head with two auxiliary, single-extruder heads. This decision was made to allow one large, multi-color print that utilizes the full print bed space, or to allow several smaller prints utilizing a fraction of the bed with just a simple adjustment. Figure 16 illustrates our initial carriage design.

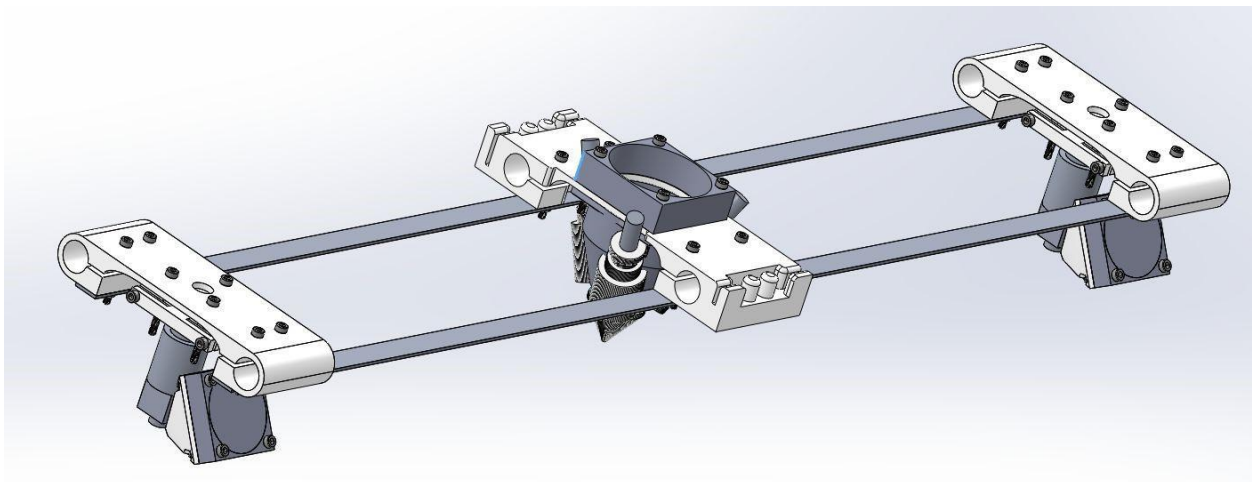


Figure 16: SolidWorks model of print head carriages

4.1. Diamond Carriage

Designed around a digital model for the Diamond Hotend provided by RepRap.me, the carriage is designed to hold the assembly with the nozzle of the Diamond Hotend on the x-axis of the carriage. It is also designed with the Diamond Hotend in a fixed mounting position, which the auxiliary carriages will adjust to match the same z-height (or offset from the print-bed). The carriage was designed to sit in-between the Diamond Hotend fan and the mounting bracket, allowing for the hotend components to add strength to the carriage. The width and length of the carriage was decided upon as the minimum dimension needed to avoid interference with the linear bearing clamping mechanisms. The ends of the carriage are designed to hold the belt that will drive the movement of the hotend, with this design the belt will interlock with itself by

looping around a boss and being press fit into an undersized slot. Figures 17-19 illustrate this design.

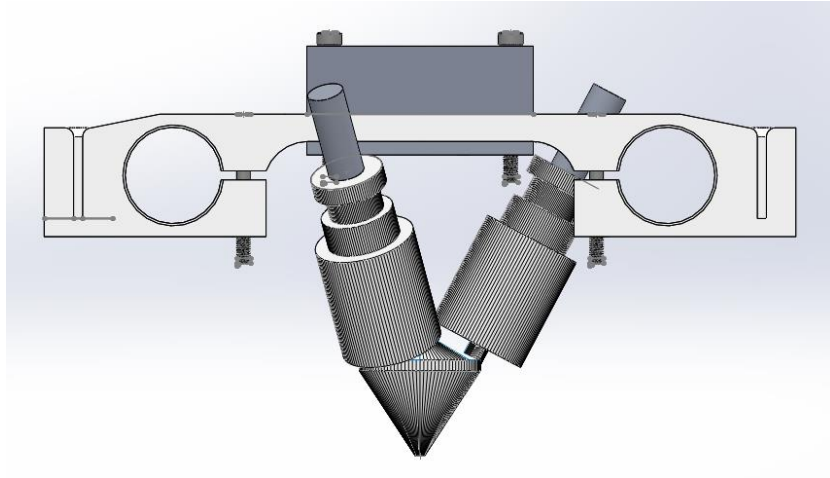


Figure 17: Side view of Diamond Carriage

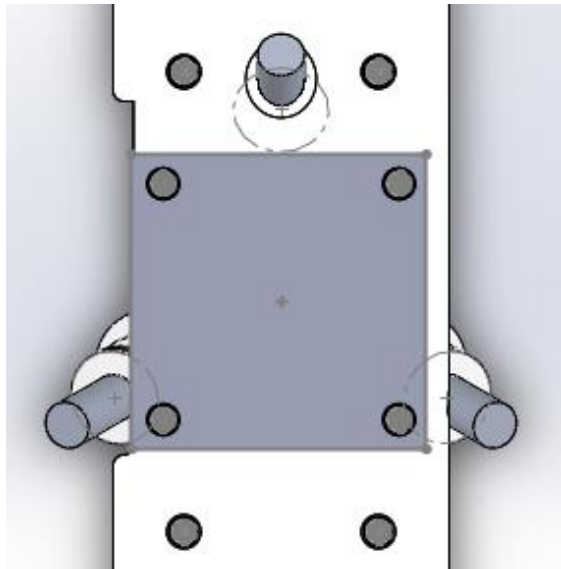


Figure 18: Top view of Diamond Carriage

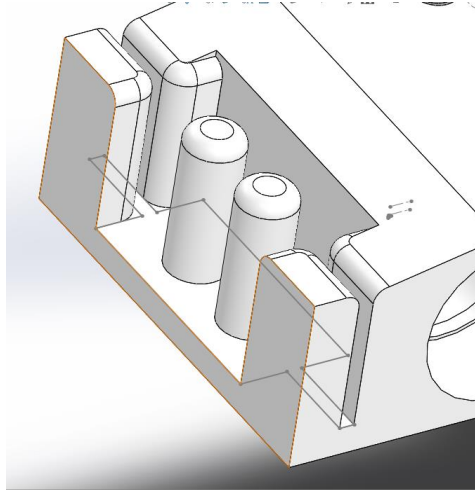


Figure 19: Section view of slotted belt fixture

4.2. Auxiliary Carriage

The auxiliary carriage is designed to have the E3D v6 hotend attach to the structure around its stock mounting location, and to have the hotend assembly adjustable within the carriage along the z-axis but fixed in the x and y directions.

The adjustment of the hotend is achieved through three M3 machine screws with 0.5mm pitch. The use of three screws improves the torsional stability of the hotend when the machine changes directions, and allows for the hotend to be kept vertical by ensuring it is perpendicular to the carriage. The pitch of the M3 screws allows a quarter turn to allow adjustment of around half of a common layer height of 0.2mm. A quarter turn was used as this measurement is easily performed with reference to the right angles of the carriage assembly, also the user can easily estimate a $\frac{1}{8}$ turn of the adjustment screws with the reference to the right angles of the carriage assembly (or about $\frac{1}{4}$ of a common print layer height). Springs are present around the adjustment screws between the hotend and the carriage to maintain the z-height adjustment and prevent the hotend from shifting during printing. The nuts of the adjustment screws are held in place by the assembly to allow the user to adjust the nozzle height with one hand, and allows for improved accuracy with the height adjustment. The lengths of the adjustment screws and springs are based on the designed height of the Diamond Hotend, allowing for variances in vertical part dimensions from the manufacturer of up to 3mm. Figures 20 and 21 illustrate this design.

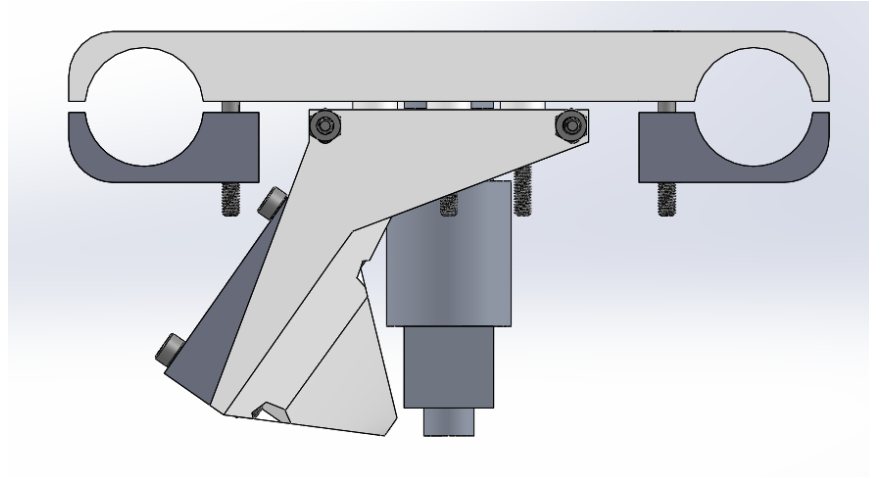


Figure 20: Side view of auxiliary carriage

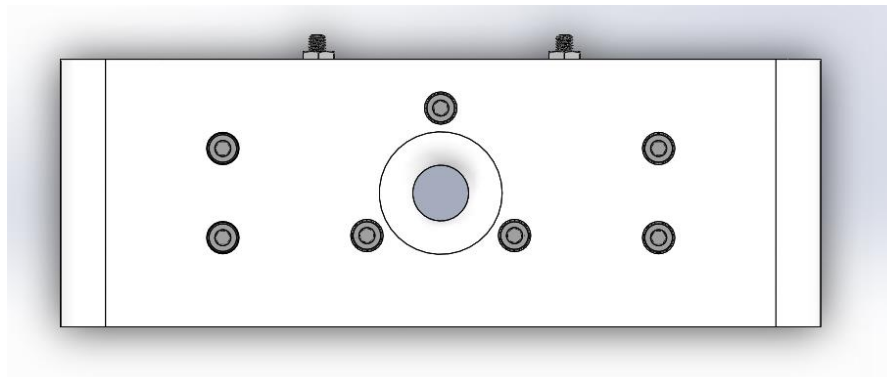


Figure 21: Top view of auxiliary carriage

The E3D v6 hotend is secured into place with two machine screws and a clamp. The screws on the clamp are also used for the attachment of a filament-cooling duct, which allows for higher quality prints with materials such as PLA. The carriage for the auxiliary hotends was also made wider than needed to allow for the use of additional linear bearings to further stabilize the carriage. Because the bearings are also in the same location as on the main carriage, the auxiliary and main carriages can be accommodated on the same linear shaft. Figure 22 illustrates more clearly, how the auxiliary carriage is assembled.

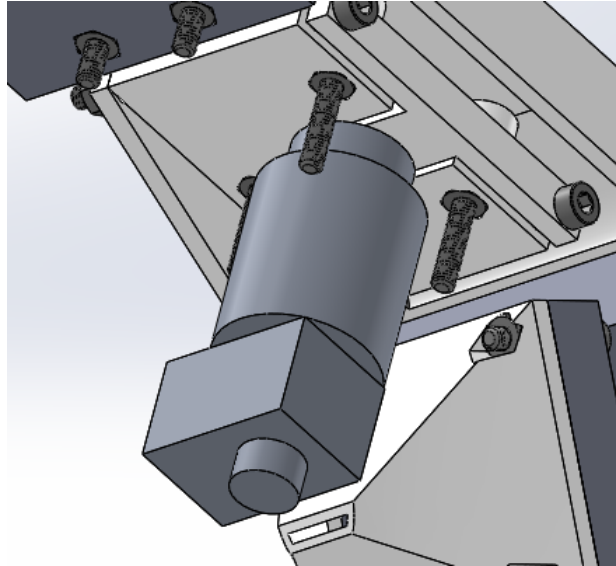


Figure 22: Bottom view of auxiliary carriage assembly

4.3. Diamond to Auxiliary Carriage Assembly

The different carriages connect with aluminum flat bar and the existing bolts used in securing the bearings to each carriage. The bolts are slightly longer than needed for the bearing in order to accommodate the aluminum flat bar and nut. Two aluminum flat bars are used, one each side of the carriage, to evenly transmit forces driving the main carriage to the auxiliary carriages, without causing torsion of auxiliary carriage. Each aluminum flat bar attaches to each carriage with two bolts to ensure perpendicular alignment. Both aluminum flat bars add about 70g to the final assembly.

4.4. Design Revisions

The first revision of the parts was done to fix four major issues found with the first iteration prototype of our 3D printer. The first of the issues was undersized screw and bearing holes, which were corrected with an added 0.2mm to the diameter of the screw and bearing holes on all parts. This eliminated the need for post processing after our carriages had been constructed (through use of a 3D printer). The second issue was a lack of structural rigidity in several locations along the carriages including the cooling fan ducting of the auxiliary carriages, the middle portion of the auxiliary carriages, and the middle portion of the Diamond Carriage. To improve rigidity, the wall thickness of the filament-cooling duct was doubled, the edges of the auxiliary carriage were stiffened through the addition of a structure resembling an I-beam, and the carriage thickness was increased by 3mm (doubling the original thickness). Because the completed carriages included clamping mechanisms that were printed larger than anticipated, the next fix required decreasing the thickness of the auxiliary clamping mechanism and adding additional clearances between the two parts. The last revision involved adding additional

clearances for the mounting bracket of the main carriage because, in the original carriage design, the cooling fan duct included with the component interfered.

The second round of revisions was required to address two new major issues. The first of these issues was the cracking of the bearing clamps on the auxiliary hotends due to the delamination of print layers, exacerbated by the force of the clamps. This issue was resolved by creating a two-piece clamp, allowing the bearing to be clamped without the bending of printed material. The next issue to be addressed was the deflection of the 8mm rods supporting the carriages. Because the rods were deflecting more than the height of one print layer, not addressing this issue would mean compromising print success. The rods thickness was increased from 8mm to 12mm, which required a redesign in the carriages to accommodate larger diameter bearings. Ultimately, 6mm was added to the length and height of each carriage.

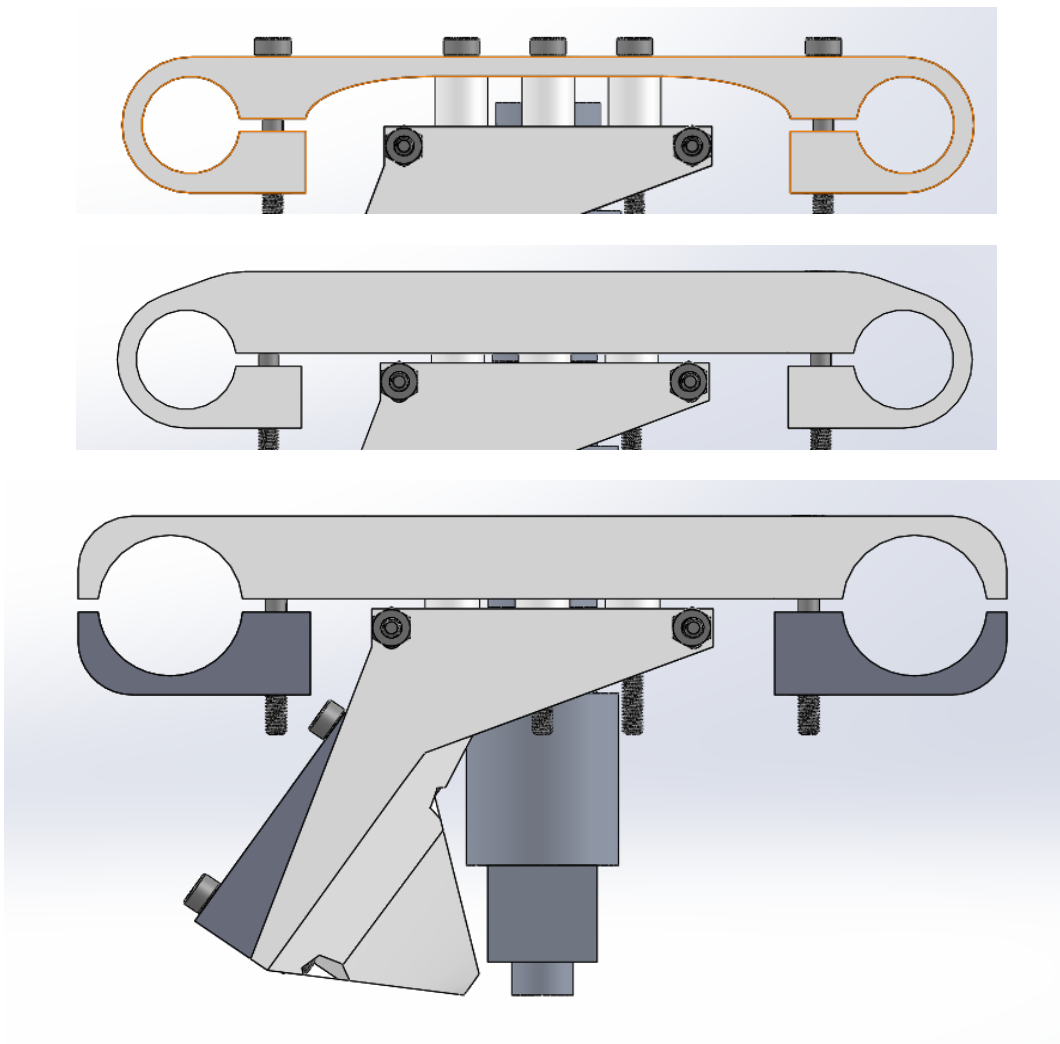


Figure 23: Side-View of Design Revisions, from top to bottom

5. Methodology

In order to test our models, we wanted to utilize a standard across which our different prints could be compared to each other and to the original model. We wanted to consider print quality, consistency in prototype features between the different print heads, and the color mixing capabilities of the Diamond Head. Using models available online, we developed testing methodology to evaluate the qualities important in proving the success of our design. Unfortunately, due to time constraints caused by revisions to the printer and incomplete print processes, the majority of testing was done in a qualitative fashion. Large sets of data could not be obtained.

5.1. Testing

Various tests were performed in order to evaluate the different operations of the print heads. The print heads can function in two different configurations: simultaneous printing and multi-colored CMY color mixing. Simultaneous printing involved using multiple hotends to print multiple copies of the same part simultaneously. Due to the design of the printer and the use of two different hotend models, it was required that the printed parts be checked for consistency across the different hotends. The color mixing operation used only the Diamond Hotend to mix cyan, magenta, and yellow filament into a desired print color. Color mixing was tested through the mixing capability of the extruded colors.

5.1.1. Simultaneous Printing

The purpose of the simultaneous printing tests was to show the ability of the multiple hotends to print the same part in a similar quality. We tested part consistency to ensure that parts could be printed at the same time and from different heads, without loss of functionality from inherent hotend differences

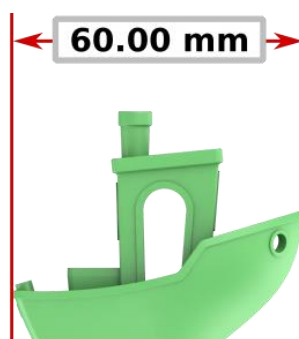


Figure 24: 3D Benchy model (obtained from 3DBenchy.com, 2016)

The primary tests for the repeatability of printed parts between the print heads was completed with the 3DBenchy model, shown in Figure 24. This model had been used to compare print quality of different 3D printers as well as different filament by other organizations in the past, and is somewhat of a standardized testing model. Its various model features made it ideal for testing qualitative aspects, such as print quality. The model includes features used for

measuring inner and outer cylindrical dimensions, linear dimensions of printed space and open space, and angular dimensions. Examples of the various dimensions are shown in Figures 25 to 27.

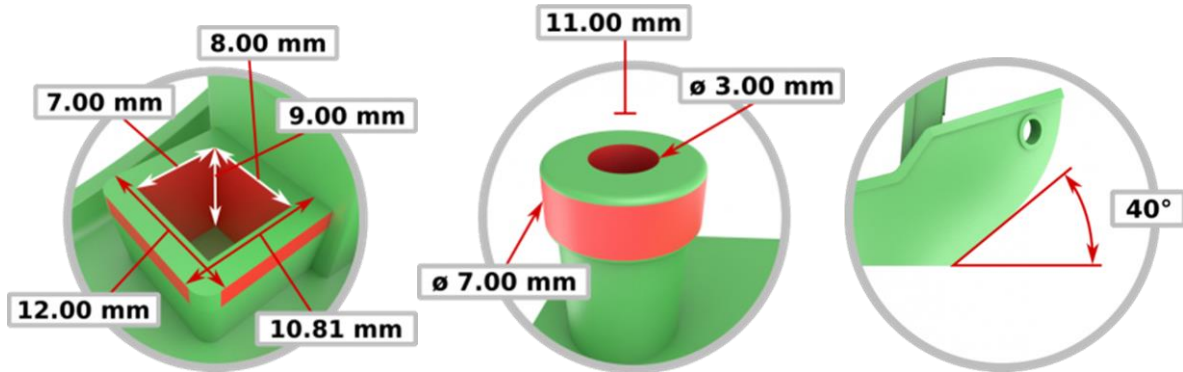


Figure 25 (left): Linear dimensions of printed and open space

Figure 26 (center): Inner and outer cylindrical dimensions

Figure 27 (right): Angular dimension of part. (3DBenchy.com, 2016)

Along with the 3DBenchy model, different models as shown in Figures 28 and 29 were used to test additional qualities between the different heads. These models were used for determining overhang capabilities, where the filament is printing at increased angles over open space. Still other models were used for further testing of fine details, where the print quality between the heads could be tested.

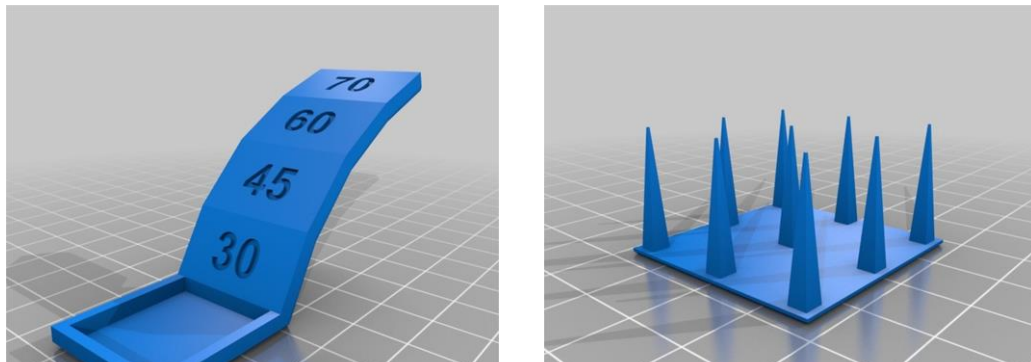


Figure 28 (left): Overhang test model for increasing overhang angles

Figure 29 (right): Fine detail testing model for quality of fine details. (Obtained from MAKE at thingiverse.com, 2014)

5.1.2. CMY Color Mix Printing

The purpose of the CMY color mix printing tests were to gather data on qualitative aspects of using three base stocks of filament (in this case yellow, cyan, and magenta). Qualitative testing was conducted through testing the color mixing capabilities of the hotend, and through comparing the created prints against unmixed single color prints for finished part quality.

Qualitative testing for the color mixing capabilities began with creating samples of various color mixes, such as the blocks shown in Figure 30. The samples of color mixes allowed for observations on the mixing quality of the various stock filament colors. In these tests, thoroughly mixed colors without any ‘toothpasting’, as seen in Figure 31, were desired. A successful mixed color would show no indications of color mixing having taken place, and appear in quality and color as though it were printed from a single-color spool of filament. We printed 16 different colored swatches, a number chosen based on software limitations.

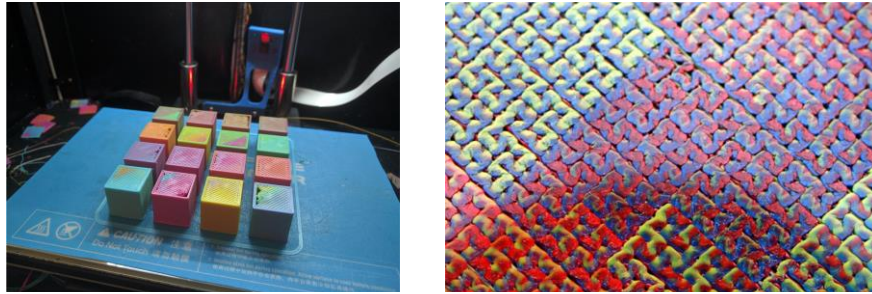


Figure 30 (left): Example of possible color samples (obtained from [reddit.com/r/3DPrinting](https://www.reddit.com/r/3DPrinting), 2016)

Figure 31 (right): Toothpasting effect, note individual colors in print lines (obtained from richrap.blogspot.com)

The multi-color printing ability of the Diamond Hotend was tested using various two-color prints, such as those shown in figure 32. These models allowed for use to test the ability of the hotend and control of the printer to create models with two clearly defined colors as a single part. The success of the print could be determined through interfacing between the different colored sections, absence of gradients within the colors, and overall part quality compared to those seen in the previous single-color testing.



Figure 32: Example of multi-color Benchy prints (Obtained from 3DBenchy.com, 2016)

6. Results

Among the first objects printed with our 3D printer were test cubes. These cubes are designed with precise 20mm dimensions on all sides, and, assuming perfect print quality, the resulting object should be 20mm on all sides. Because a 3D printer can never produce models to the exact dimensions specified in the computer, these test cubes are used to assess the tolerances on a printer and help to fine-tune any hardware feature that could produce more precise print dimensions. In our initial test cubes, the X direction measured 20.17mm (0.85% accurate), the Y direction measured 20.25mm (1.25% accurate), and the Z direction measured 20.42mm (2.10% accurate). Our initial test cube is shown in Figure 33.

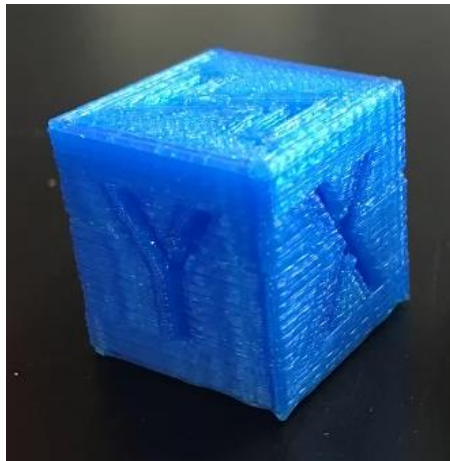


Figure 33: Initial test cube

A major portion of successfully constructing any 3D printer is calibrating the settings that work best for the specific hotends, extruders, and even filament reels being used in a print. As such, a majority of our testing was meant to assess the current state of print quality based on initial settings and make adjustments to improve print quality. Where test cubes helped us to determine major discrepancies in dimensions, a simple arrangement of pillars was used to aid in the identification of excessive stringing within prints. Stringing occurs when filament oozes from the hotend nozzle when the hotend is moving between disconnected portions of the same print. As indicated from the initial stringing test shown in Figure 34, stringing was a major issue that needed to be addressed continually throughout the duration of our test prints. While we were able to greatly reduce the interference of stringing in the quality of our final prints, further trial and error must be conducted to eliminate the issue.

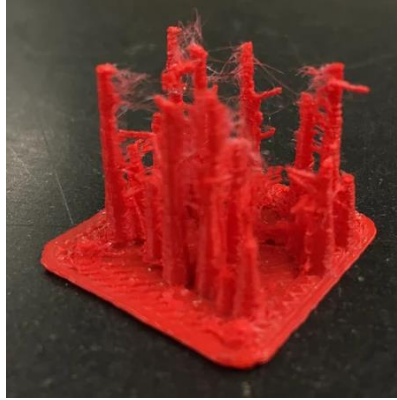


Figure 34: Stringing test, displaying significant stringing between separate sections in a single model

Yet another method for assessing print quality looks at the adhesion between layers, and the resulting ability of a printed model to arch or overhang with limited support material. Initial overhang test prints failed, resulting in complete layer separation at about a 60-degree angle. One example of this failure is shown in Figure 35. Subsequent tests, after making adjustments in extrusion rate, hotend temperature, and bed temperature, resulted in complete overhang test prints, shown in Figure 36. While these tests were complete in that the print did not fail, Figure 37 shows the underside of the overhang test print where layer separation is still evident. These subsequent tests improved the ability of our printer to achieve about a 70-degree angle with overhang successfully. Further testing could improve the printer's ability to complete overhang tests up to about an 80-degree angle.



Figure 35: Failed initial overhang test print

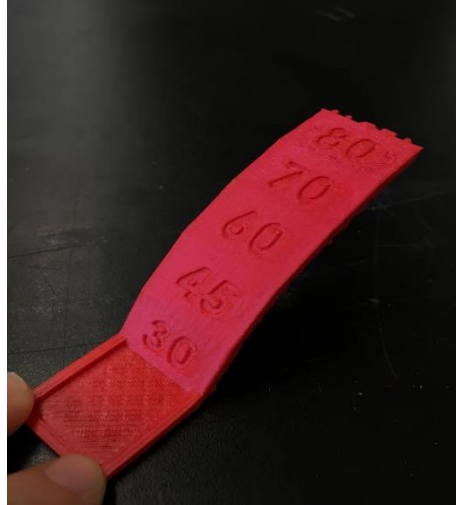


Figure 36: Complete overhang test print

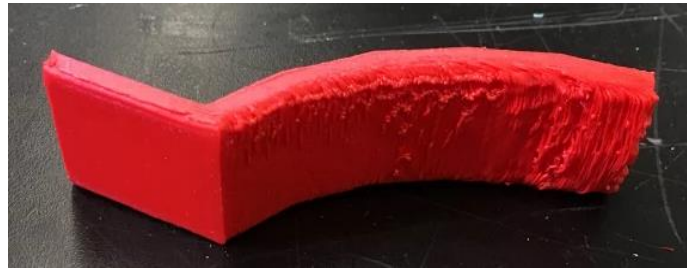


Figure 37: View of the underside of a completed overhang test, indicating insufficient layer adhesion above a 70-degree angle

Because an important feature of our printer is its ability to print large scale, we needed to test its ability to print using as much of the available print bed space as possible. For this test, we chose a basic grid 18in long and 9in wide. While not a large-scale print in volume, the success of this print did serve as a proof of concept for future large-scale prints. Additionally, while our bed surface was flat and level enough to allow for the successful completion of this large-scale print, some areas of the print- particularly in the middle- indicated that the bed was not an entirely smooth surface as print height varied. Figure 38 shows the large-scale grid while being printed.

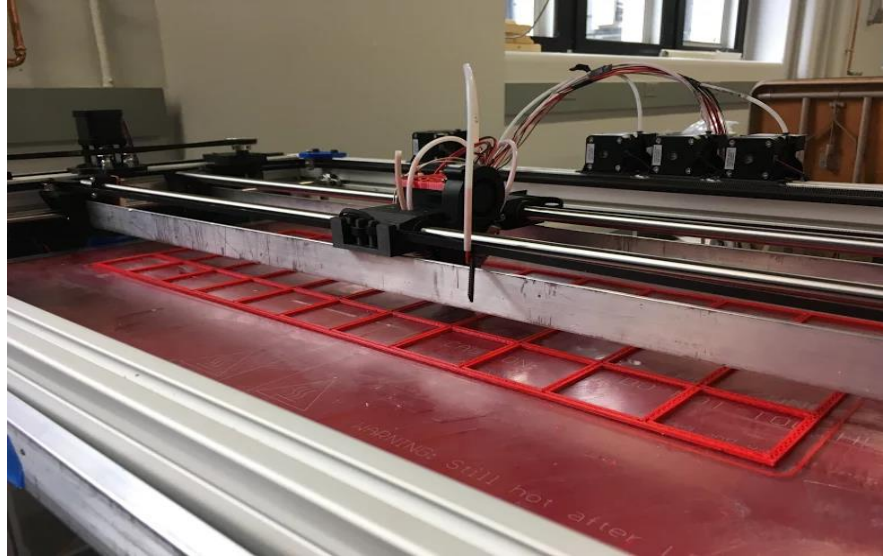


Figure 38: Progress picture of the large-scale grid being printed

As explained in our Methodology, the 3DBenchy model was developed as a way to test the overall capabilities of 3D printers. Sixty 3DBenchy test prints were attempted, to varying degrees of success. Early 3DBenchy tests, some of which are shown in Figure 39, included evidence of issues with stringing and overhang, as well as bed adhesion and wobbling within the layers (which was addressed by the Platform group through bed stabilization, not through adjusting print settings). Poor bed adhesion resulted in incomplete prints, as shown on the far left 3DBenchy in Figure 39, or layer shifting, as shown in Figure 40. When the first layers of a 3D print are not completely secure on the print surface, as the print cools, these layers can completely remove themselves and cause subsequent print layers to extrude without adhering to anything. The wobbling within layers is most easily visible in the rightmost 3DBenchy in Figure 38.



Figure 39: Early 3DBenchy test prints



Figure 40: Failed print due to poor bed adhesion, causing layer shifting

While not all the 3DBenchy prints were successful, and other failed prints can be found in the Appendix, we were able to complete smooth, consistent, and ultimately successful prints. Figures 41 and 42 show the front and top views, respectively, of three 3DBenchy models printed simultaneously from each of the three print heads. These tests were among the last ones completed, and indicated that the printer is capable of printing high quality models across all print heads simultaneously.



Figure 41: Front view of successful 3DBenchy test prints

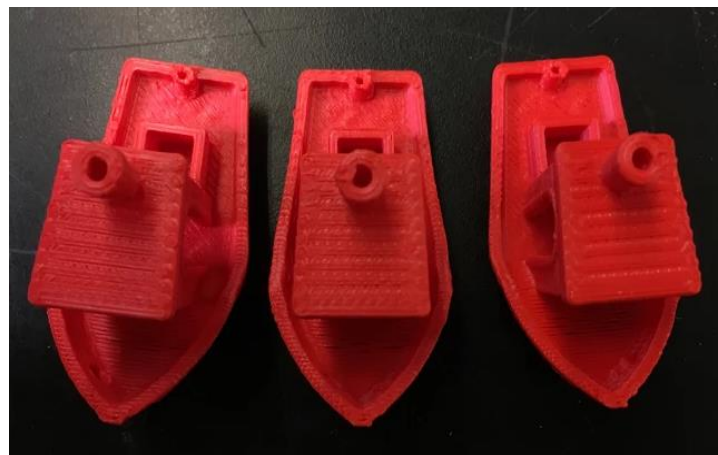


Figure 42: Top view of successful 3DBenchy test prints

Color mixing and multi-color printing were two other critical components of our 3D printer design. Color mixing required a lot of work to be done on the printer's firmware in coordination with the Controls group. Ultimately, we were able to successfully print 16 different color swatches demonstrating the full array of colors possible with our printer design. Figure 43 shows the swatches for the 12 rainbow colors. Additionally, four different brown swatches were created (one magenta dominant, one yellow dominant, one cyan dominant, and one containing equal percentages of all three-filament colors).



Figure 43: Color swatch examples for CMY color mixing

To test multi-color printing capabilities, we began with a small, two-color die. An initial failed attempt (which can be found in the Appendix) lacked a purge tower for transitioning between magenta and yellow filament colors. As a result, the die contained almost no visible magenta, because the amount used in the print was minimal compared to the amount of yellow used and thus yellow could not be purged enough (from the hotend) within the print for magenta filament to begin to be extruded. Figure 44 shows the second, successful print. After manually adding a purge tower, the magenta pips on the die became clearly visible against the yellow base, resulting in a successful two-color print.



Figure 44: Successful two-color die

The next multi-color print required more color switching within layers. Figure 45 shows the magenta and cyan frog printed as our next attempt at a multi-color print. The adhesion between both colors was exemplary throughout the print, resulting in little to no separation between colors or layers and an overall smooth print surface. While we did encounter problems

with stringing, there were no issues with overhang in this print.



Figure 45: Two-color frog print

As a final step in our testing, we wanted to create a model that not only used a mixed color or two filament colors in one print, but also combined both features in one design. For this test, we chose a two-color cat model and elected to use a mixed orange and a mixed green as the two colors making up the model. This print was, unfortunately, not as successful as the two color frog, but was complete enough to serve as a proof of concept and jumping off point for future testing of the mixed and multi-color applications of our printer.

Overall, mild stringing occurred on this print (as on the frog), and there were no major issues with overhang. The major problems can be found in the surface texture of the print and the consistency of the mixed colors. Unlike in the magenta and cyan frog, the orange and green of the cat model did not adhere well together, and the resulting surface of the model is lumpy, with visible separation between colors. Additionally, the green color appears slightly more yellow at certain points throughout the print. This color consistency issue is most likely due to problems with the extruder responsible for the blue filament losing traction on the filament being fed into the hotend and not extruding, as opposed to an issue in the firmware confusing which color should be extruded.



Figure 46: Two-color, color-mixing print example

7. Conclusion

Ultimately, we were able to construct a working 3D printer with many novel features previously unavailable in commercial printers. Our printer is capable of printing one object in a print volume of 36in x 18in x 9in, two simultaneous copies of the same object in a print volume of 18in x 18in x 9in, and three simultaneous copies of the same object in a print volume of 12in x 18in x 9in. All print volumes achievable with this printer are significantly larger than the print volumes of standard commercial 3D printers, which was the basis for determining if our printer was capable of large-scale prints.

Because of our mechanically linked carriage design, the printer is able to print multiple copies of the same product simultaneously. For our tests, we linked three print heads together and conducted test prints using standardized 3DBenchy models. After assessing these models for quality and consistency across the three heads, we determined that the printer could successfully print comparable parts simultaneously, without a reduction in quality within any part. Based on our tests, linking additional carriages to print four or more products simultaneously would be successful, provided the printer hardware is able to handle operating all the heat sinks and extruder motors.

Configuring the firmware to accommodate mixed color and multi-color prints required more time and trial and error than was initially anticipated. We were able to successfully blend sixteen different colors, but the practicality of using these colors in a design proved more difficult as the blended colors showed inconsistency within a print. Further testing should be done to better evaluate the success and usability of color mixing in large-scale prints.

Multi-color prints using colors as provided directly from filament reels proved more successful. While these prints did encounter some issues with stringing, print settings can be adjusted to minimize these negative effects, and overall the print quality was not severely impacted.

This project was ambitious, but we were able to construct a large-scale printer capable of simultaneous printing, as well as mixed and multi-color printing. As mentioned previously, there is still a ways to go in configuring printer settings before all features of the printer are comparable to

the quality of other commercial 3D printers. Most notably, stringing must be reduced to improve surface quality of finished models. Additionally, color mixing and using mixed colors in printed models should be improved until print surfaces are smooth and colors are consistently mixed throughout a model.

After addressing these issues, future projects could work to further improve the design overall. Working more in conjunction with the other groups (or perhaps taking control of the entire project), adjustments to the controls board and to the 3D printer structure could allow for control of more print heads, more Diamond Hotends, and better usage of maximum print volume. Future projects could also look into adapting the current 3D printer system to accommodate other manufacturing methods, including a NC machine. A quick transition between additive and subtractive manufacturing methods on the same system could greatly improve manufacturing processes. Other methods of 3D printing- such as powder or pellet- could also be tested with some adjustments to the current design, to compare print quality or even combine features of various 3D printing methods. A majority of our testing was conducted using PLA filament. Further testing could experiment with other filament types including high temperature (such as Nylon or Polycarbonate), or even novelty materials. While a variety of more experimental print filaments exist on the market today, further project iterations could explore the usage of materials- from candy or cookie dough, to new engineering materials that replicate the look or mechanical properties of popular construction materials.

References

AliExpress. (2016, March 1). *3D printer Reprap Makerbot MK8 Full Metal Aluminum Alloy Bowden Extruder for 1.75MM Filament Left way side* [Bowden Extruder for 3D printer available online].

Dyze Design. “DyzEnd-X Hotend” Retrieved from <https://dyzedesign.com/shop/hotends/dyzend-x-hotend/>

E3D-Online. (2014) “E3Dv6 Release Announcement and Design Details” Web. Retrieved from http://e3d-online.com/index.php?route=extras/blog/getblog&blog_id=21

Grieser, F. (2016, January 14). PLA vs ABS: Filaments for 3D Printing Explained & Compared. Retrieved February 14, 2017, from <https://all3dp.com/pla-abs-3d-printer-filaments-compared/>

“History of 3D Printing: The Free Beginner’s Guide.” *3D Printing Industry*. Accessed October 10, 2016. <http://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/history/>

Hughes, Bill, & Wilson, Greg. “3D/additive printing manufacturing: A Brief History and Purchasing Guide.” *Technology & Engineering Teacher* 75, no. 4 (2015).

Klarmann, Alexander. (2015) “Kickstarter: Two Great Hotends for 3D Printers” All3DP. Web. Retrieved from <https://all3dp.com/solution-for-multi-color-multi-material-3d-printers/>

Landry, Taylor. (2016) “Extruders 101: a Crash Course on an Essential Component of Your 3D Printer” Matterhackers. Web. Retrieved from <http://www.matterhackers.com/articles/extruders-101:-a-crash-course-on-an-essential-component-of-your-3d-printer>

Landry, Taylor. (2015) “All Metal Hotends - Out with the Old, In with the New” Matterhackers. Web. Retrieved from <https://www.matterhackers.com/articles/top-reasons-to-upgrade-to-an-all-metal-hotend>

“Material Jetting”. (2016). Retrieved from <http://www.me.vt.edu/dreams/material-jetting/>

Ooznest. (2017, February 10). *Hexagon 3D Printer All Metal Filament Hot End Nozzle - 1.75 & 3.00mm - RepRap* [Hotend Nozzle for 3D printer available online].

Palermo, E. (2013, September 19). “Fused Deposition Modeling: Most Common 3D Method”.

Web. Retrieved from <http://www.livescience.com/39810-fused-deposition-modeling.html>

Ponsford, M., & Glass, N. (2014, February 14). The night I invented 3D printing. Retrieved February 14, 2017, from

<http://www.cnn.com/2014/02/13/tech/innovation/the-night-i-invented-3d-printing-chuck-hall/>

“Powder Bed Fusion”. (2016). Retrieved from

<http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/>

Stevenson, Kerry. (2015) “Bowden or Direct? A Primer on Extruder Styles” Fabbaloo. Web. Retrieved from

<http://www.fabbaloo.com/blog/2015/11/11/bowden-or-direct-a-primer-on-extruder-styles>

“What is 3D printing?” (2016). Retrieved from <http://3dprinting.com/what-is-3d-printing/>

Williams, Linda D. “Additive Manufacturing or 3d Scanning and Printing,” in *Manufacturing Engineering Handbook*. New York: McGraw-Hill, 2015.

“3D Printer Filament Comparison”. (2016). Web. Retrieved from

<https://www.matterhackers.com/3d-printer-filament-compare>

Appendix

This table reviews a range of different materials often used for 3D printing. Information presented includes the name of the material, the range of temperatures that the extruder must heat to print the material, the range of temperatures that is recommended that the bed be kept at during production, and average yield strengths of the material.

Material	Ext Temp (Low)	Ext Temp (Hi)	Bed Temp (Low)	Bed Temp (Hi)	Yield Strength MPA
PLA	180 C	220 C	20 C	55 C	55-72
ABS	220	235	80	110	18.5-51
Nylon	235	270	60	80	50-94.8
PET	230	255	55	70	56.5-62.3
TPE	210	225	20	55	--
Soft PLA	220	235	20	55	--
TPU	240	260	40	60	--
Polycarbonate	270	310	90	105	59-70
BendLay	210	240	20	55	--
MoldLay	170	180	20	55	--
PVA	170	190	45	45	--
HIPS	220	230	50	60	28.7-56.2

Assembly Instruction for Extruders and Hotend Carriages

This first set of instructions reviews the construction of the Titan Extruder Assemblies, which push the material through the filament tubes.

Titan Extruder Assembly Instructions

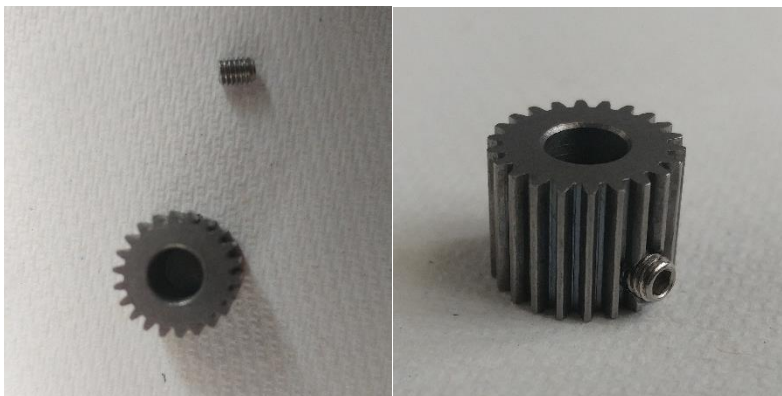
1. Slide Bowden Tube into the Idler Arm.



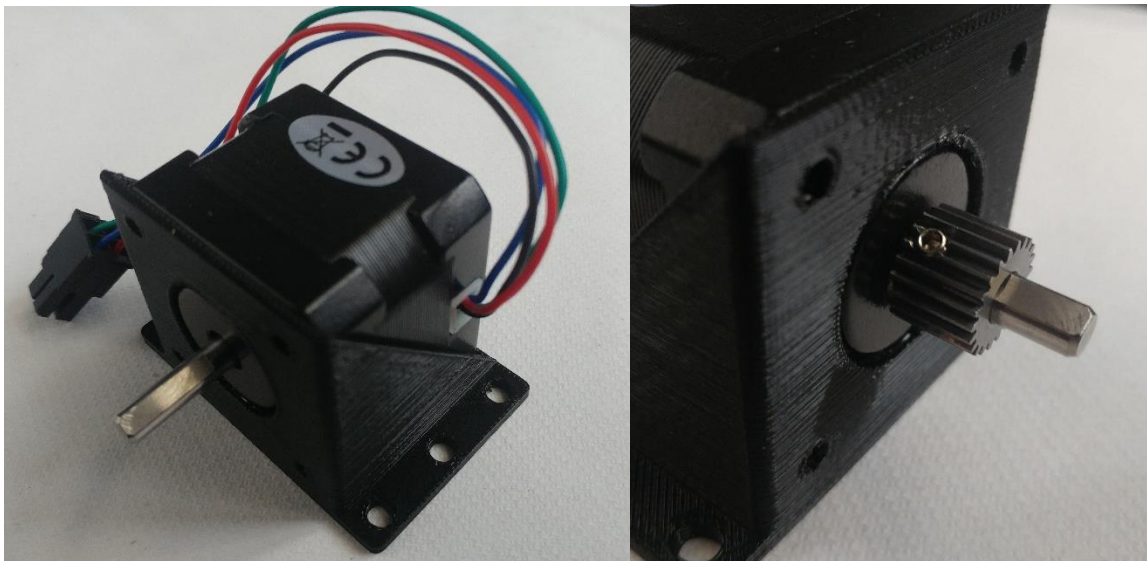
2. Screw the hexagonal nut all the way up the M4 thumbscrew.



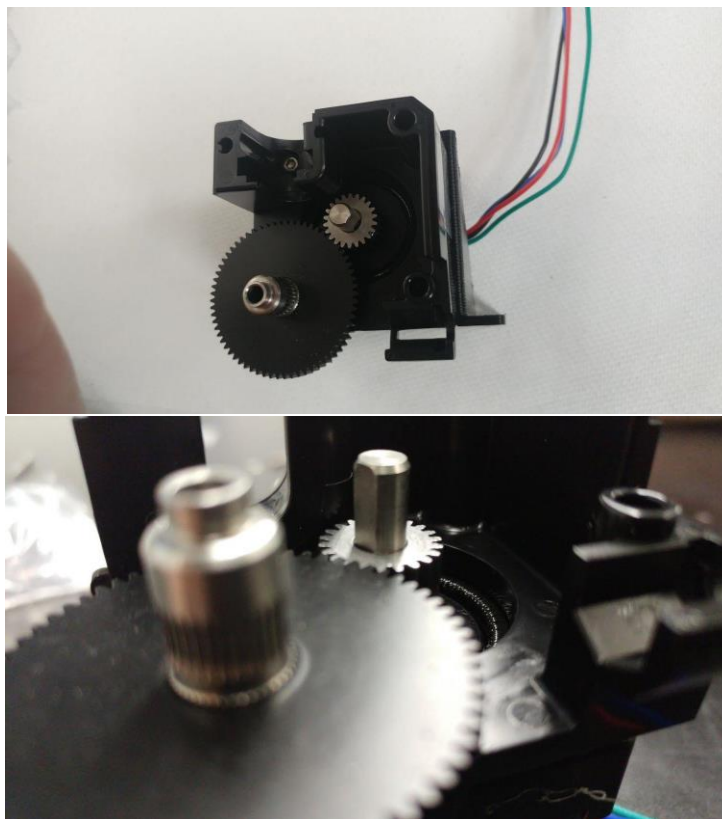
3. Loosely tighten the Pinion Grub Screw into the Pinion Gear.



4. Place the Mounting Plate and Stepper Motor together as shown. Attach the Pinion Gear to the motor shaft, aligning the Grub Screw with the flat section of the shaft, and tighten.



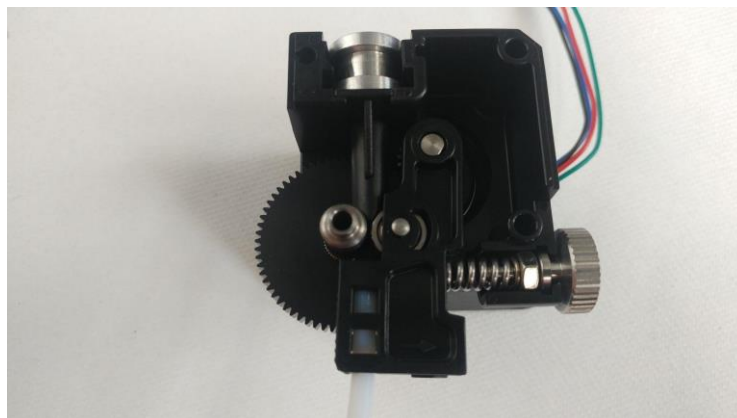
5. Place extruder body with gear on mounting plate, secure with m3x8 screw as shown. Make sure that the tops of both gears are level with each other.



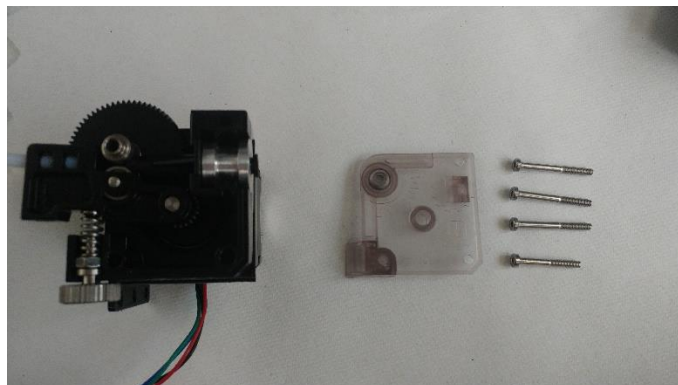
6. Place the Bowden Adaptor and Filament Guide in the slots on the Extruder Body as shown.

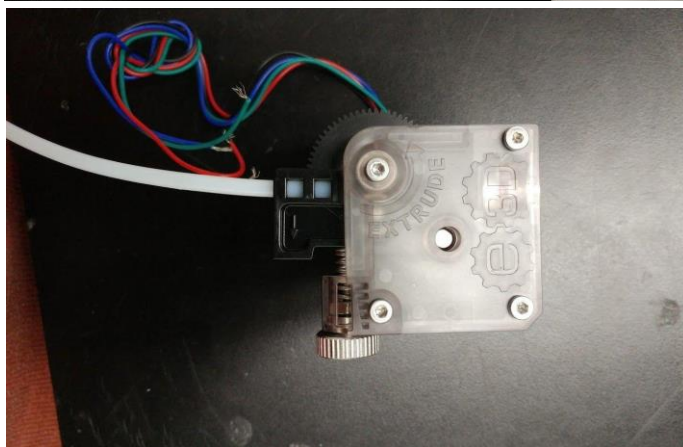


7. With the spring on end of thumbscrew, align other end of spring with bump on idler arm. As one piece, place on the Motor assembly as shown.



8. Take the plastic cover, one m3x25 screw, and three m3x30 screws. Place the cover on the assembly, the rounded corner nearest to the Idler Arm, and attach with screws. M3x25 is nearest the Bowden adaptor, the rest in the rest. (NOTE: Before screwing in, the screw heads should all be at the same height). Screw until flush, do not over tighten.





Auxiliary Hotend and Carriage:

This section details the construction of the E3D single extruder hotends and carriages.

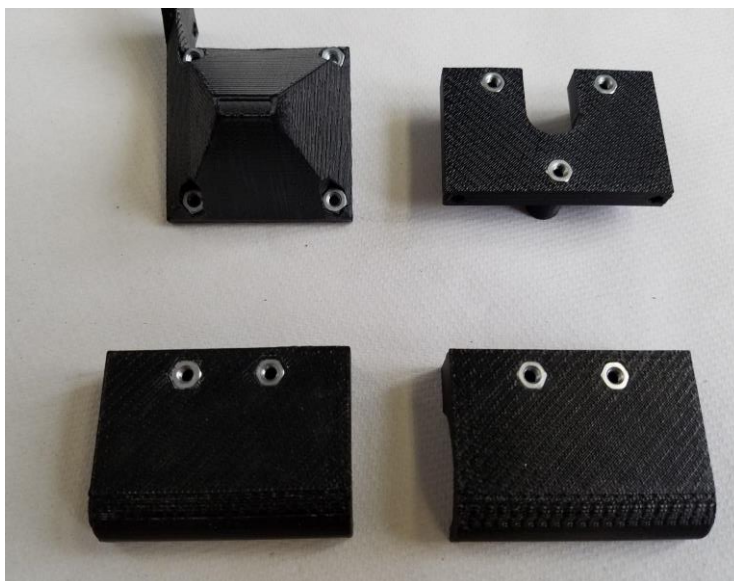
Hotend

Begin by following E3D assembly instructions available on their wiki page: http://wiki.e3d-online.com/wiki/E3D-v6_Assembly

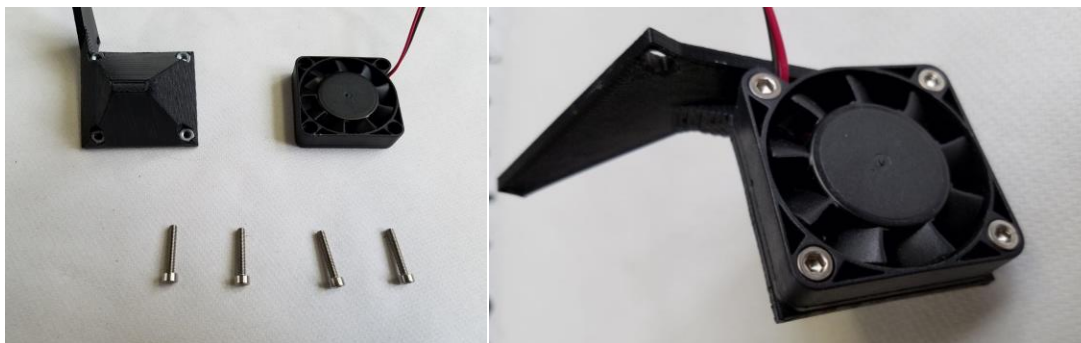
Carriage Assembly



8. Press fit the hexagonal nuts into the respective holes as shown. Eleven m3 hex nuts are used; four on the carriage, three on the hotend holder, and four on the cooling fan shroud. (NOTE: nuts on the cooling fan shroud are pressed into place using the assembly screws.)

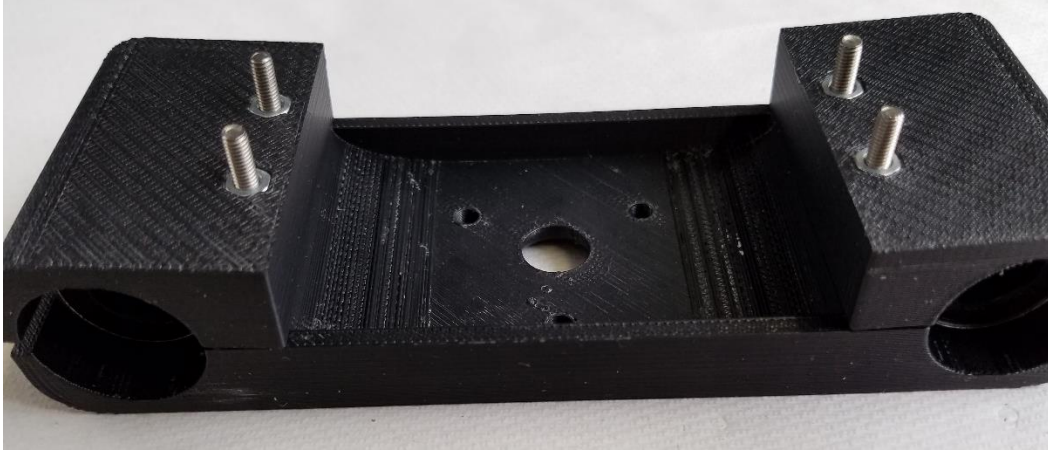


9. Take the m3x18 screws and screw the 40mm fan onto the Cooling Fan Shroud. The wire should be oriented as shown.



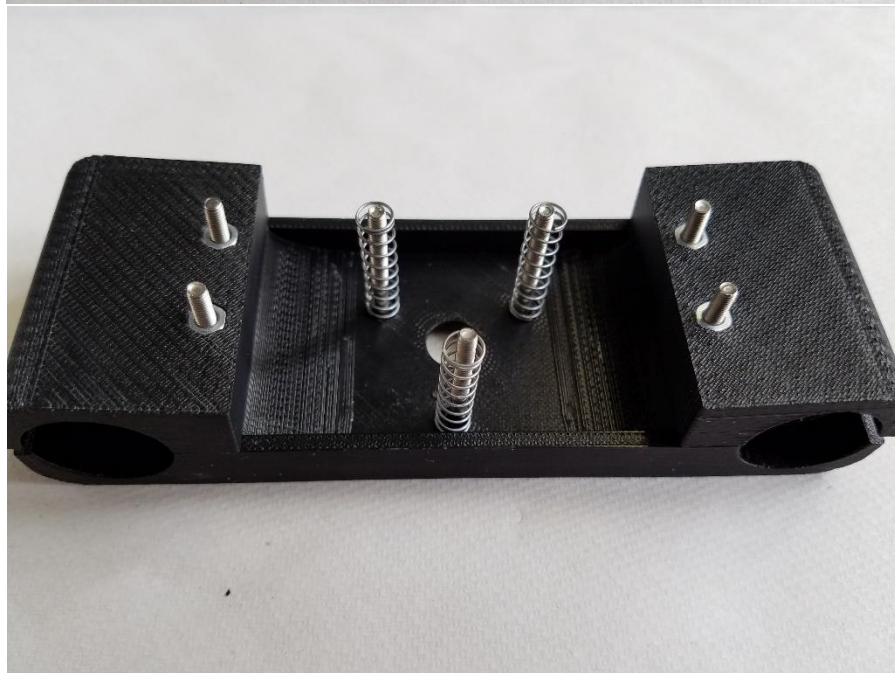
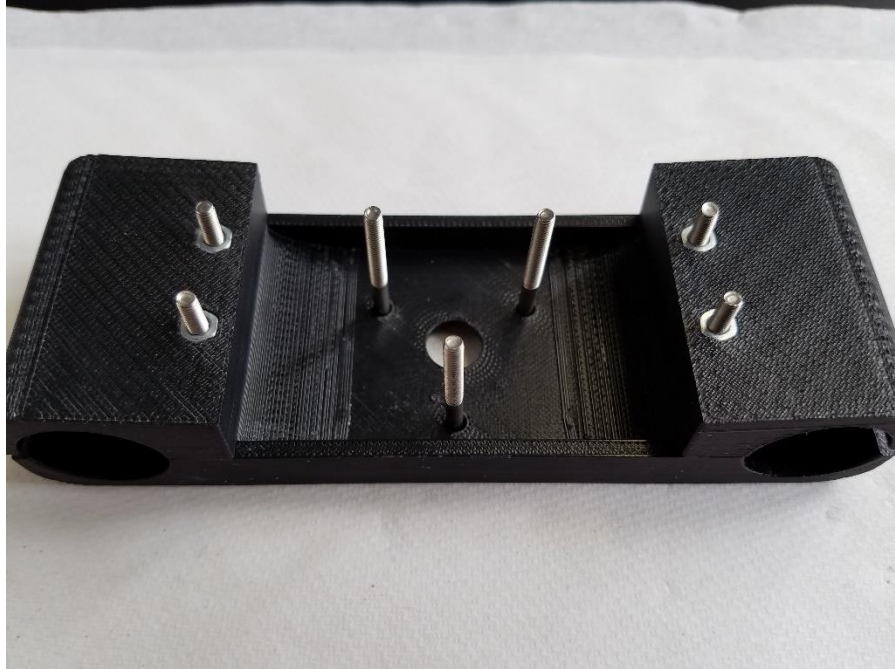
10. Take the two Bearings and place one on each side of the Carriage assembly, inside the spaces provided. Screw four m3x30 screws into the assembly and tighten the bearings into place. (NOTE: Bearings should be tight enough to not be moved by hand, but should not be overtightened.)



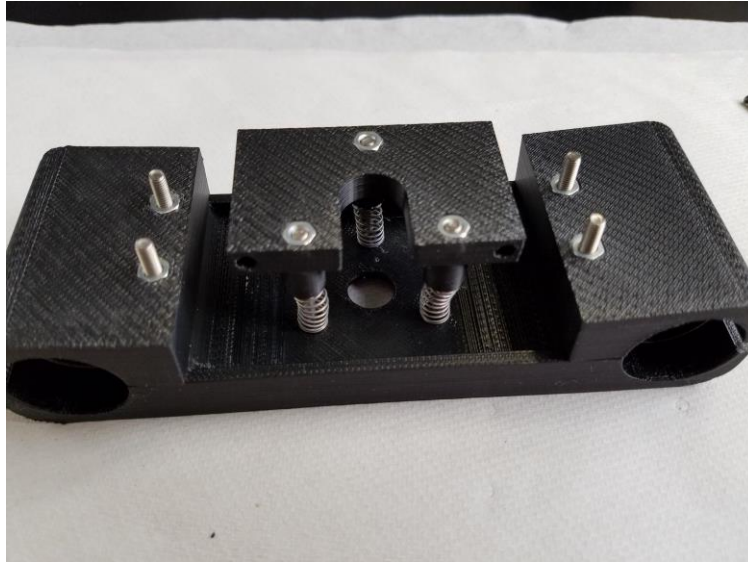


11. Place three m3x30 screws into the holes in the center of the Carriage. Place a spring around each screw.

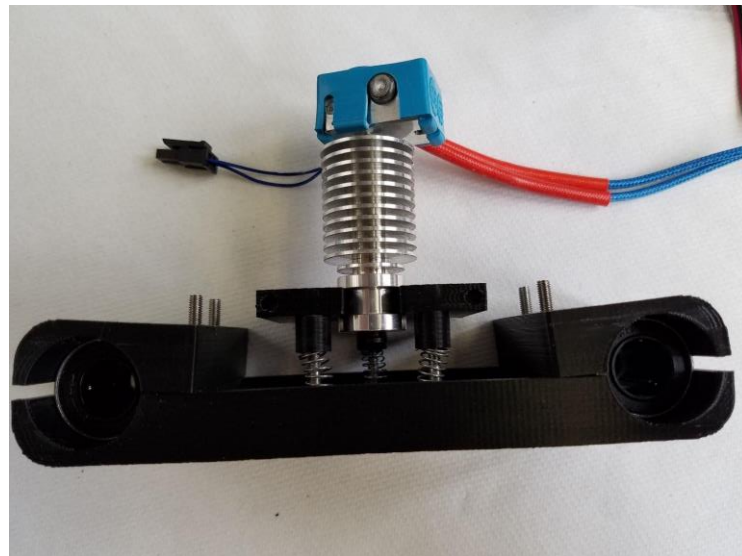




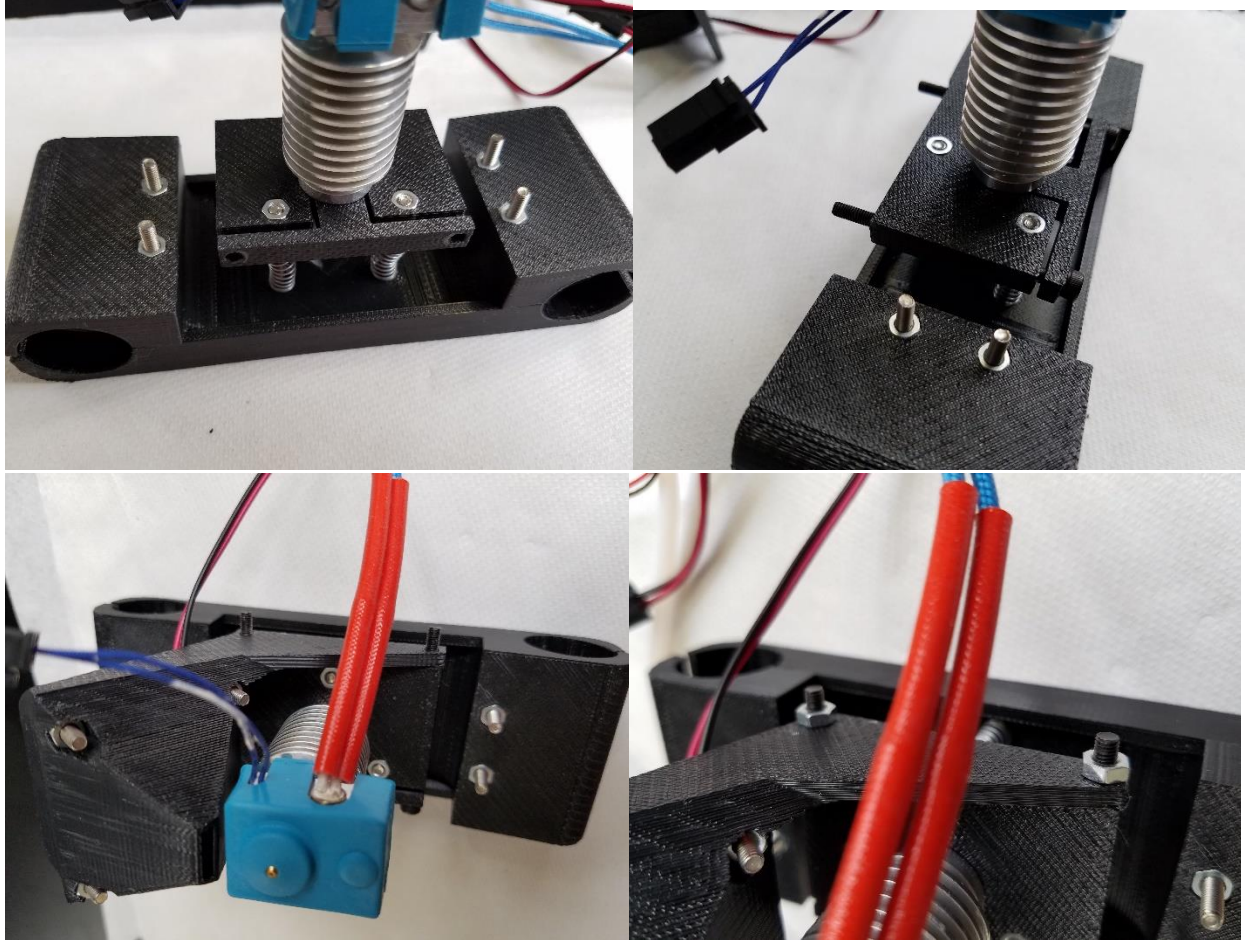
12. Attach the Hotend Holder to the three center screws of the assembly.



13. Place Hotend into the Hotend Holder as shown.



14. Put the m3x45 screws through the holes of the Hotend Clamp, then slide the screws through the Hotend Holder and place the filament Cooling Fan Shroud on the protruding screw ends. (NOTE: Rotate the hotend so the heater block does not interfere with the cooling shroud.) Tighten the assembly using an m3 nut on the end of each screw.



Diamond Hotend and Carriage

This section details the assembly of the Diamond triple extruder hotend and carriage.

Hotend Assembly

Begin assembly by following steps 3-11 of the documentation provided by RepRap for assembly of the Diamond Hotend: http://reprap.org/wiki/Diamond_Hotend

Carriage Assembly



9. Press fit the hexagonal nuts into the respective holes as shown along the sides of the Carriage. Four m3 hex nuts are used.

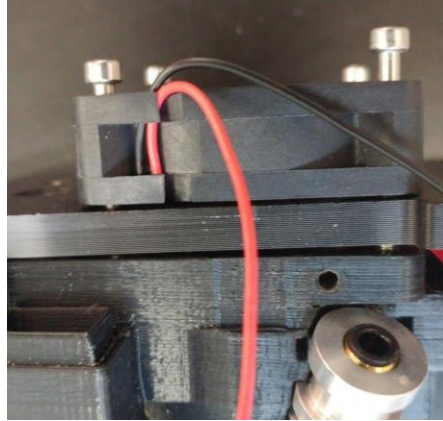


10. Take the four Bearings and place two on each side of the Carriage assembly, inside the spaces provided. Screw four m3x30 screws into the assembly and tighten the bearings into place.

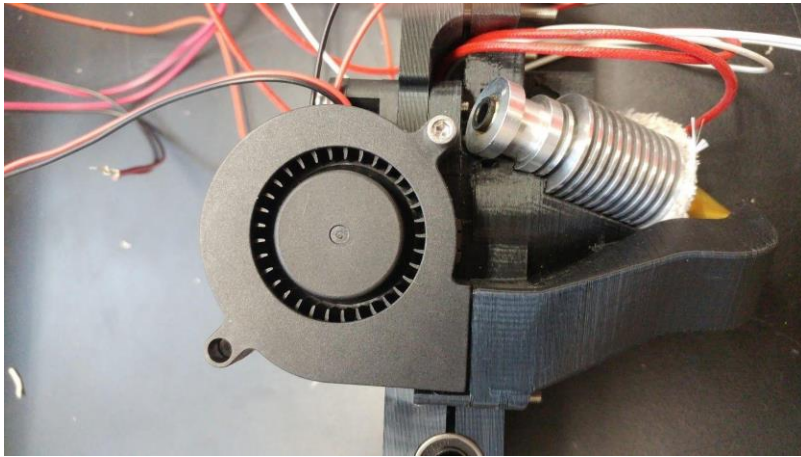
(NOTE: Bearings should be tight enough to not be moved by hand, but should not be overtightened.)



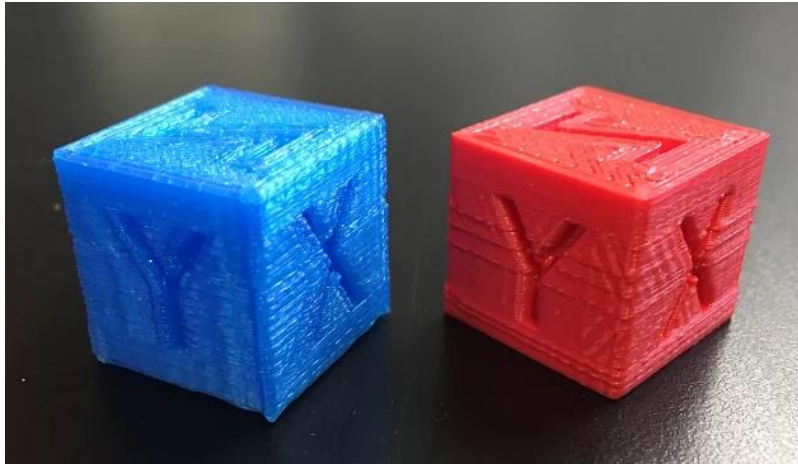
11. Place the Diamond Hotend assembly under the Carriage assembly, aligning the holes in the top of the Hotend assembly with the holes in the center of the Carriage assembly. Now align the 40mm Radial Fan, the wires along the side with the cooling duct, with the holes on top of the Carriage Assembly. Attach the three assemblies with the m3x30 screws. (NOTE: Be sure to route wires through the notch in the Cooling Shield before bringing the assemblies together.)



12. Align the output of the Blower Fan with the inlet of the cooling duct as shown. Screw the Blower Fan to the assembly using an m3x30 screw.



Printed Part Portfolio



Test cubes in cyan and red PLA.



Red PLA bolt and screw.



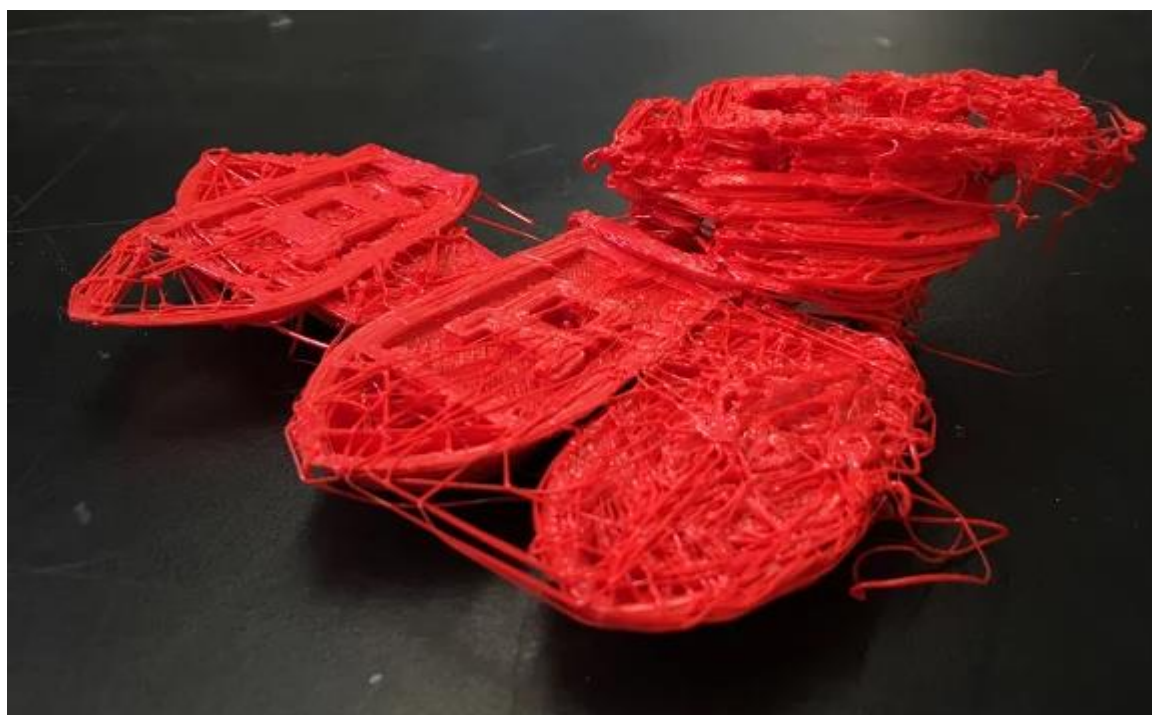
Red PLA die.

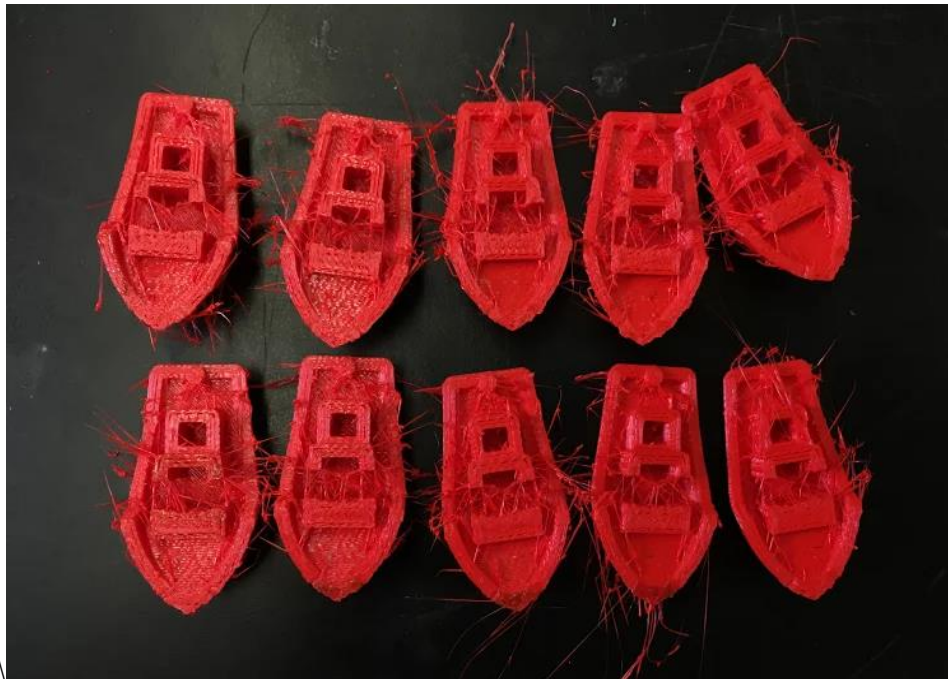


Cyan and red PLA 3DBenchy test prints



Small-scale red PLA hairy lion





Vairous Examples of failed red PLA 3DBenchy test prints.



Three large-scale hairy lions, printed simultaneously



Full range of PLA mixed and multicolor prints, including brown shades.



Red PLA Gompei Goat Statue