# Palm Print: Portable 3D Printer

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*Submitted to the Faculty of*
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*in partial fulfillment of the requirements for the*
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*in Mechanical & Materials Engineering*

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# Abstract:

Palm Print is a compact, portable 3D printer designed as an introductory device for prototyping components. The target consumers are students in K-College programs. To develop this product, we first researched required components, kinematic schemes, and thermal and material extrusion properties. Three mechanical prototypes using the CoreXY methodology were produced, and underwent analysis using Ansys, verifying the designs would not fail under normal operating stresses. An Arduino and Klipper-based electronic and software structure was created and tested for optimal kinematic and thermal profiles for the belts, pulleys, motors, and extruder. Overall, we delivered a product unseen in the market using optimal manufacturing, design, analytical, and systems engineering methods.

# Introduction:

First developed in the 1980s, 3D printing is the earliest form of additive manufacturing, a process of manufacturing that constructs layers of material to form the structure of a computer-generated model. Since its inception, 3D printing has become a greater alternative to subtractive manufacturing techniques that involve the removal of material to form parts. 3D printing has quickly become a staple in manufacturing due to rapid manufacturing speeds, easier production of challenging designs, and lower production costs. These advantages are apparent when smaller, plastic-based parts are suitable for the overall design. Larger parts and metallic parts; however, still use subtractive manufacturing such as Computer Numeric Control (CNC) machines due to sizing and material constraints of 3D printers (Wong, & Hernandez, 2012). With the lowering cost of 3D printers over time, additive manufacturing has been adopted by a wide range of industries such as aerospace, automotive, fashion, food, materials science, and biomedical devices (Huang, Liu, Mokasdar, & Hou, 2013). From 1995 to 2010, 3D printer sales have seen a compound annual growth rate of 26.2%, as detailed in Figure 1 below.

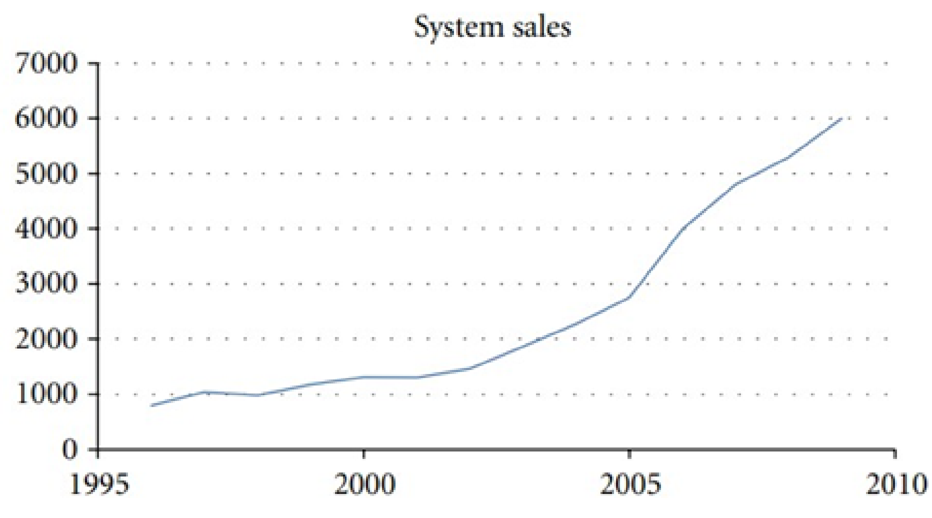



Figure 1: Sales growth of 3D printers from 1995-2010 (Wong & Hernandez, 2012)

Companies within these industries can create 3D models using Computer Aided Design (CAD) software and convert them to a Standard Tessellation Language (STL) file. The STL file is a file format that stores the surfaces of the CAD model and slices them into a form of code that helps the 3D printer translate the design into layers. These surfaces are formed through the linking of numerous mapped triangles that can produce flat and angled surfaces. A greater number of triangles mapped results in models with higher definition and resolution. The code the STL file turns into is known as G-Code. G-Code is formed through slicing the triangles of the STL files into a kinematic format that any printer can use. This format plots the three dimensional points of extrusion of a specified part. The user can set specific slicing settings that affect the printed part's quality. These settings include the layer height, infill density, and support settings. Once the STL file is sliced, the user can transport the code into a USB drive or SD card, and insert it into the printer's USB or SD card port. The file is then selected in the user interface of the printer and then sent to print using the G-Code (Wong & Hernandez, 2012). The method of creating a 3D printed part with the steps mentioned can be seen in Figure 2 below.

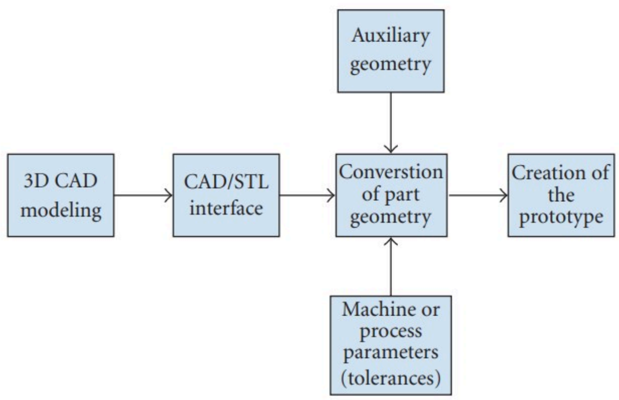



Figure 2: 3D Printing Process (Wong & Hernandez, 2012)

Observing the lowering cost and upwards trends in sales and ease of use, our group intends to tap into an unseen part of the market. Portable printers are not widely sold, and the Palm Print aims to be a cheap, easy to use, portable printer for our target user base. Our intended customer demographic is K-12 students looking to learn additive manufacturing as well as potential industry settings. Many schools have adopted 3D printers for classes and extracurriculars such as robotics, but these printers are too large to take back to school. Through Palm Print, students can take their printing ideas from school and transport and expand them at home. Students can also use Palm Print for robotics at school, and then create a new toy at home. Companies in the field of engineering and manufacturing can also have a 3D printing device that can come with them to any business trip, or be used in house. These can be more small-scale prototypes, or manufacturing small parts such as gears and rods. Endless possibilities for mechanical prototyping and creativity are realized when anyone has greater access to a device that can make any digital design come to the physical world.

# Chapter 1: Background

## 1.1: Types of 3D Printers

### 1.1.1: Fused Deposition Modeling (FDM)

Fuel Deposition Modeling (FDM) printing involves the use of material filament, an extruder, and the hot end to produce the layers of material. In FDM printing, the solid filament is fed by the feeder motor into the extruder's hot end. The hot end then uses its high temperature to liquify the filament. The liquified material is then extruded onto the print bed where it solidifies as a layer. Layers are then continually stacked until the final design is reached. Figure 3 below demonstrates the printer head’s configuration and layering process. Common materials used in FDM printing filaments include Polylactic Acid (PLA), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) (Wong, & Hernandez, 2012).

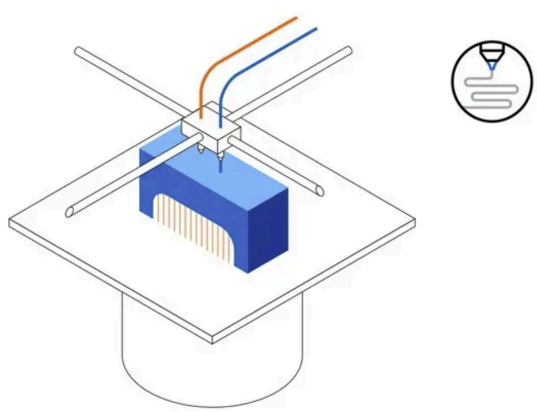


Figure 3: FDM Printing Process (Formlabs, n.d.)

### 1.1.2: Stereolithography (SLA)

Stereolithography (SLA) printing was the first 3D printing method adopted. SLA Printing sees an ultraviolet laser make contact with a resin bath housed on top of the print bed. When the laser makes contact with the resin, the resin undergoes reactions that cause curing or solidification. The laser, specified by the STL file, will be precisely pointed to certain areas within the resin bath where the layers are created (Wong, & Hernandez, 2012). This process is detailed in Figure 4 below.

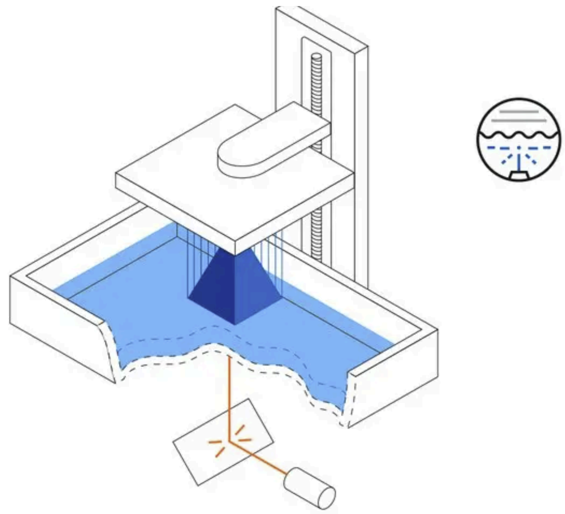


Figure 4: SLA Printing Process (Formlabs, n.d.)

### 1.1.3: Selective Laser Sintering (SLS)

Selective laser sintering (SLS) uses a laser and powdered polymers to form complex parts. SLS printers use a high-powered laser directed onto powdered polymers in a powder bed. Once the laser hits the powder it forms a melt pool. This melt pool cools and a layer is formed. The recoater then goes back over the print bed, distributing fresh powder onto the print bed. There are many different polymers used in SLS printing. The most common polymers powder is Nylon 12, but other materials such as metals, plastics and ceramics can all be used as well (Wong & Hernandez, 2012). Shown below in Figure 5 is a detailed diagram of this process.

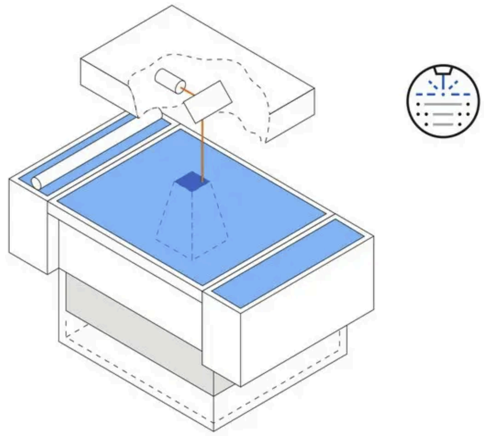


Figure 5: SLS Printing Process (Formlabs, n.d.)

## 1.2: 3D Printer Parts

### 1.2.1: Extruders

The extruder pushes the filament from the spool to the hot end to be melted. The two main types of extruders are bowden and direct extruders. The differences in each type is depicted below in Figure 6.

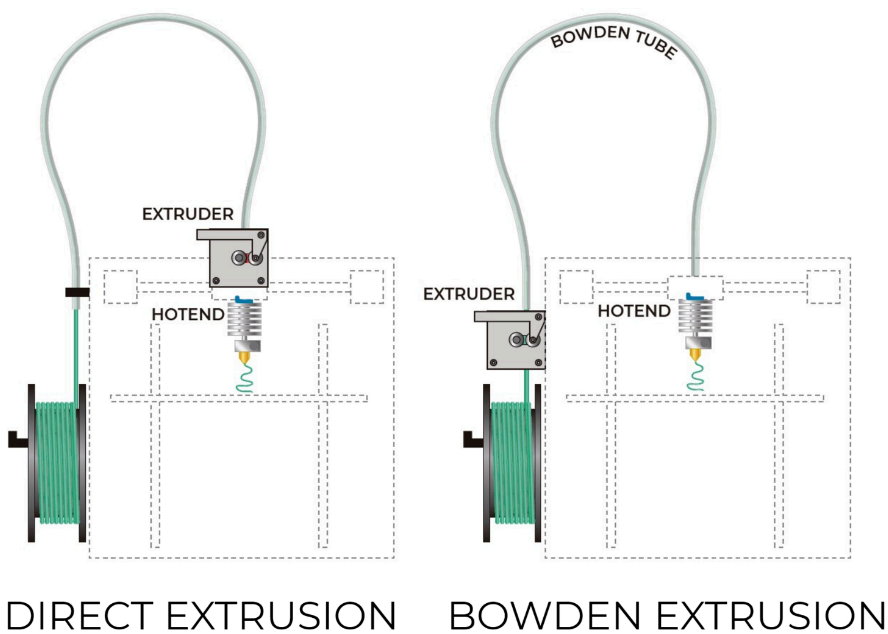



Figure 6: Direct Drive and Bowden Extruder System (Recreus, 2021)

## Bowden

A bowden extruder has the feeder motor located away and unattached to the hot end. A tube is required to guide the filament from the feeder motor to the hot end. This design is typically used in smaller printers, where a smaller and lighter hot end is desired *(e3d, 2022)*.

## Direct

A direct extruder has the feeder motor attached to the hot end. It is located before the hot end, and because it is attached, the hot end has to move with the feeder motor. An advantage of this design is greater control over the filament *(e3d, 2022).* With less distance between the feeder motor and the hot end, there is less uncertainty of how much filament is being provided at a given time. However, the mass of moving parts is increased, meaning it is less suitable for cheaper, smaller 3D printers.

## Hot End

The hot end of the extruder is responsible for heating the filament and liquifying it to be extruded onto the build plate. The hot end is made up of several components, including the cold side, heating block, heatbreak, temperature sensor, and a fan if necessary. The heater cartridge is a device made from heating coils that directly heats up the heating block. It typically outputs 30 watts, enough to heat the hotend to 300°C *(e3d, 2021).* The heating block, typically made from aluminum or copper, acts as a heat reservoir, keeping temperature stable. The cold side consists of the heat sink, made from a stack of metal fins. The design is to remove excess heat so the filament remains as rigid as possible before heating. When the filament heats up in the hot end, it expands, and if the filament in the cold side is rigid, the melted filament is forced out the nozzle. Between the cold end and the hot end is the heatbreak. Its purpose is to separate the cold side from the hot side. If the heat break is ineffective, the extruder may experience clogging *(e3d, 2021).*

## 1.2.2: Print Beds

The print bed, also known as the build plate, is the printer component the hot-end extrudes the print material on. It is important for the print bed to be flat and smooth to allow the print material to stick. Different print beds will work better for different print materials.

### Glass

Glass print beds come with two different finishes. One will be very smooth and provide strong adhesion and surface finish. The other will be textured, and will also provide good adhesion, but the part removal will be easier (*The home of E3D, n.d.)*. Both have similar performances. The surface finish for the part touching the bed plate will; however, have a texture on it. The plate with a texture will provide slightly more adhesion, due to the plastic reforming within the textured grooves. Both are low cost options that work well with PLA, ABS, TPU and nylon. Both plates provide easy part removal, as when the bed cools, the glass contracts slightly. The contraction forces the piece to pop off the print bed (*The home of E3D, n.d.)*.

### Spring Steel PEI

Similar to glass, spring steel PEI comes as smooth or textured. These properties are similar to the glass bed, as the smooth surface allows for a smooth finish on the part, while the textured surface will provide a stronger first layer adhesion. The textured plate also allows for more room in the Z-offset (*The home of E3D, n.d.)*. While part removal on the textured plate is easier, both plates are magnetically detachable from the printer and are very flexible. This provides the user with an easy part removal for either plate. These print beds are slightly more expensive, but they are compatible with PLA, ABS, PETG, TPU, and nylon.

### G10

G10, or Garolite, is the cheapest material while still supplying an optimal surface finish and adhesion for the first layer. G10 is very rigid and durable, resulting in less scratches and a longer lifespan (*The home of E3D, n.d.)*. While G10 is very durable, it is not good at transferring heat. This means anything that provides a bed temperature higher than PLA, such as ABS, will not work. When overheated, the print bed will put off toxic fumes, making it unsafe for use without an enclosure (*The home of E3D, n.d.)*. It is, however, considered one of the best materials to print PLA and nylon on. This is due to both PLA and G10 being plastic, which bond more strongly with other plastics, providing a stronger bond between the G10 print bed and PLA print (*The home of E3D, n.d.)*.

### Polypropylene

Polypropylene print beds are relatively cheap and provide the print with a smooth, glossy finish. They are also thin and bendable, providing easy part removal. Because polypropylene is a plastic, materials such as PLA, ABS, and PETG will have a stronger bond to the surface (*The home of E3D, n.d.)*. This print bed also has a high temperature resistance, meaning it can also print ABS. While it is temperature resistant, polypropylene is known to deform under repetitive heating and cooling. The material tends to scratch easily, which may appear in the print finish.

## 1.2.3: Linear Drive Systems

The linear drive system for a 3D printer is used to move either the print bed or extruder head in the X, Y, and Z directions. For 3D printers, the most common drive systems are belts with pulleys, lead screws, and ball screws (Smith, 2017). These systems are coupled with linear guides to ensure smooth movement and eliminate any twisting or rocking in other directions. The most commonly used linear guide system for 3D printers are V-groove wheels on rods, linear rods with ball bearings, and linear rails (Lily, 2023).

### Belts & Pulleys

Belts can travel long lengths and at high speeds (PCB Linear, n.d.). They operate at high efficiency and are reliable with few moving parts (Nook, n.d.). Due to the need for tensioning, belts stretch over time (Mikel et al., 2019). Because of this, they are vulnerable to slipping under high accelerations and continuous direction switching (Casillo, 2023). Because of their elasticity, they are better for smaller loads, and a gear reduction is needed for increased torque (Mikel et al., 2019). In terms of 3D printing, they are the most commonly used option for X and Y movement because they are lightweight and less expensive. Figure 7 shows an example of belts used in a 3D printer.

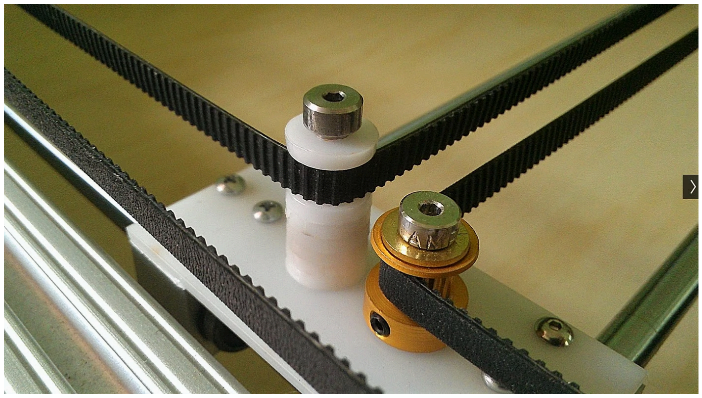


Figure 7: Belt and Pulley Assembly used for 3D Printing Applications (Siber, 2019)

## Lead Screw

Lead screws are capable of a very small step size, resulting in slower movement. Although they perform at lower speeds, they perform well with higher loads (Mikel et al., 2019). They are designed for vertical applications, in which continuous left and right movement results in faster wear (Mikel et al., 2019). Lead screws, such as the one in Figure 8, are often used for Z-axis movement in 3D printers because of their ability to achieve high precision accuracy (PCB Linear, n.d.). The precision required to achieve the smallest layer height in 3D printing ranges between 0.1mm to 0.2mm (Casabar, n.d.).

Figure 8: Lead Screw used for 3D Printing Applications (RIYIN, n.d.)

## Ball Screws

Ball screws, as seen in Figure 9, are similar to lead screws, but are more useful for large scale applications (Casillo, 2023). Since the movement is extremely smooth due to internal ball bearings, they require a braking mechanism that adds to the cost. Although they are more expensive than lead screws, they require less torque due to higher efficiency (Casillo, 2023; Nook, n.d.). Ball screws also have a high carrying capacity with a large output force (Casillo, 2023). They do well under continuous & high-speed movement, and have smooth, precise motion (Casillo, 2023). Because ball screws are more rigid than belts, they have better positioning accuracy (Casillo, 2023).

Figure 9: Ball Screw used for 3D Printing (Stevenson, 2019)

## V - Groove Bearings

A common method used to guide the linear motion of the X, Y, and Z-axes is V-groove bearing wheels. V-groove bearings are small bearings that can slide over an 80/20 aluminum extrusion part (Figure 10) (100mm Black V-slot, n.d.). Most have a V-shaped cutout on the cylindrical face, however some do not such as in Figure 10. To restrict the movement to be strictly linear, the bearings need to clamp the beam they are sliding on or be clamped between two linear rods. V-groove bearings and rods are prone to potential issues with precision and accuracy due to rotation and rocking (3D Kywoo, 2021). The V-groove and rod design is generally less expensive compared to other linear motion systems such as linear rails and as a result is very common among 3D printers (3D Kywoo, 2021). One drawback is that the bearings wear over time, requiring replacement (3D Kywoo, 2021).

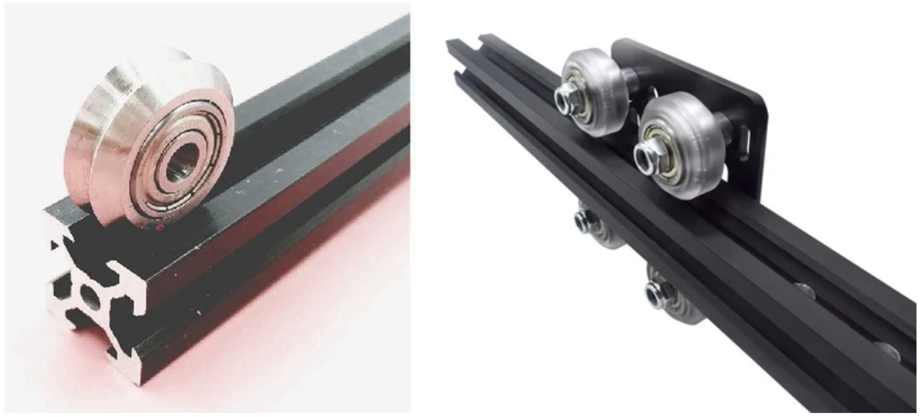


Figure 10: V-groove wheels on 2020 Aluminum (left) and bearings without V-grooves clamped for stability (right) (1000mm Black V-slot, n.d.; Black 2020 Aluminum., n.d.)

## Linear Rails

Another method of restricting linear movement is linear rails. Linear rails offer a higher level of precision and stability (Hooper, 2022). Using linear rails results in less backlash than linear rods or v-groove systems, and they are relatively easy to mount, making them a desirable choice for 3D printer designs (Kondo & O'Connell, 2022). Due to the way the rails are shaped, shown in Figure 11, the carriages are restricted to linear motion in one direction, eliminating any rocking (Industrial Quick Search, n.d.). The main drawback of linear rails is their higher cost and weight compared to the V-groove and rod system (Kondo & O'Connell, 2022).

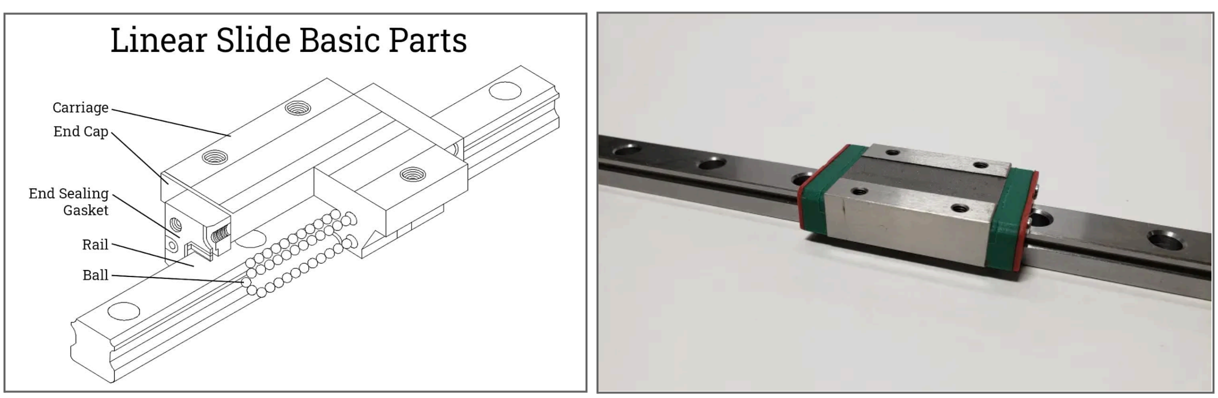



Figure 11: Linear rail cross section (left) with assembled rail (right) (Hooper, 2022; Industrial Quick Search, n.d.)

### Linear Rods

Linear rods used with ball bearings provide another option for 3D printer linear motion. While less expensive than linear rails, linear rods with ball bearings are generally less stable and require two parallel rods in order to restrict the motion to be strictly linear (Florian, n.d.). As a result, they are more difficult to mount than linear rails. Linear rods also require clamps to hold them in place as seen in Figure 12, adding another component to the design (Florian, n.d.). This design can be a compromise between cost and performance, but may not offer the same level of precision and consistency as linear rails.

Figure 12: Linear rod with clamp applied at one end (Florian, n.d.)

## 1.2.4: Motors

### Driver Motors

Driver motors are responsible for moving the extruder and the build plate. As 3D printing requires high precision for consistent and accurate detail of parts, driver motors tend to be stepper motors. For cartesian 3D printers, the number of degrees of freedom is identical to the number of motors. For a majority of printers, at least three driver motors are required, as they are printing in three dimensions.

### Feeder Motor

The feeder motor moves filament into the hot end of the extruder. As discussed earlier, the feeder motor can either be attached directly to the extruder, or located away from the extruder, where it moves filament through a guiding tube. This motor can either be a conventional DC motor or a DC stepper motor. Conventional DC motors are more efficient, although they offer less control than stepper motors, reducing the control of the feed rate. Common feeder motors include the NEMA 14 and 17 motors, as these motors provide sufficient torque and are cost efficient.

## 1.2.5: Power Supply Unit (PSU)

The power supply unit (PSU) provides power to vital electrical components such as the motherboard, extruder, motors, fan, and limit switches. The PSU supplies the microcontrollers with sufficient power to allow for motion of the belts and Z-axis extruder at acceptable speeds. It also provides the feeder motor with sufficient current to extrude the filament through the hot end, as high torque is required for pushing material through the Bowden extruder (Team Xometry, 2022) .

## 1.2.6: Microcontrollers

The microcontroller is the brain of the printer and is responsible for translating the path generated in the STL file to the stepper motors. Three types of microcontrollers were evaluated based on size, computing power, and cost. The Manta M4P board and SKR Pico both require a Wi-Fi Raspberry Pi to communicate with Klipper. The Raspberry Pi 0 2W provides adequate computing power for a small 3D printer and Wi-Fi (2W - 2nd generation, Wireless) at half the size of the Raspberry Pi 3 or 4.

1. Arduino Uno / Mega (Figure 15)
2. Manta M4P (Figure 13)
    a. With Raspberry Pi 0 2W (Figure 16)
    b. With Raspberry Pi 3 / 4 (Figure 17)
3. SKR Pico V1.0 (Figure 14)

a. With Raspberry Pi 0 2W (Figure 18)
b. With Raspberry Pi 3 / 4 (Figure 18)

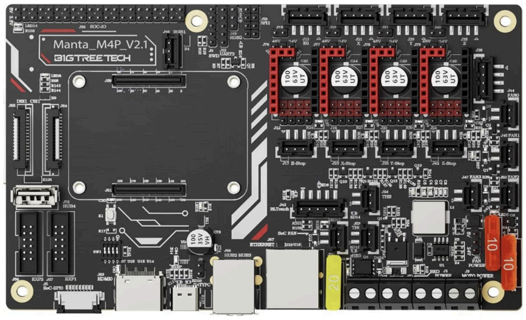



Figure 13: Manta M4P (BIGTREETECH, 2024)

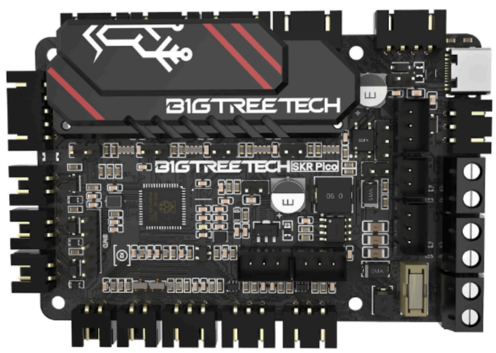



Figure 14: SKR Pico V1.0 (BIGTREETECH, 2024)

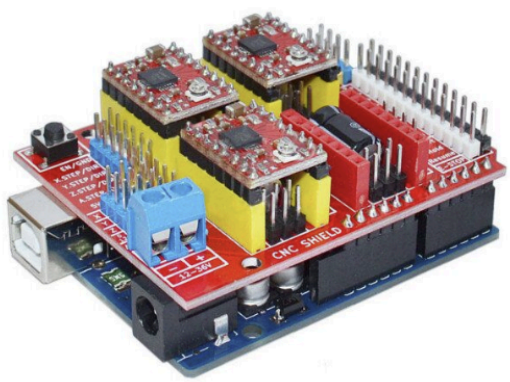



Figure 15: Arduino Uno + Shield (Dow, 2021)

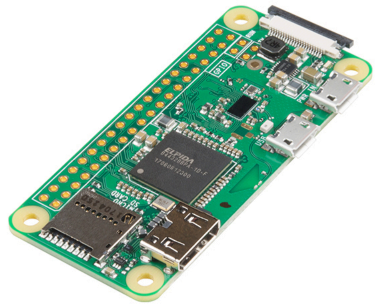


Figure 16: Raspberry Pi 0 2W (Raspberry PI, 2017)

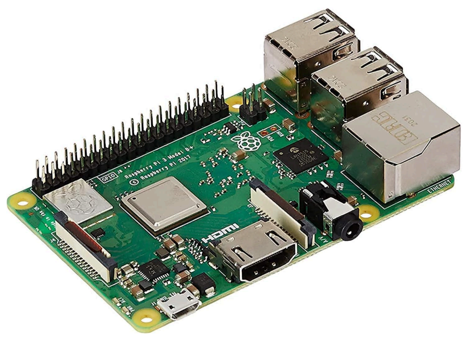


Figure 17: Raspberry Pi 3 / 4 (Raspberry PI, 2017)

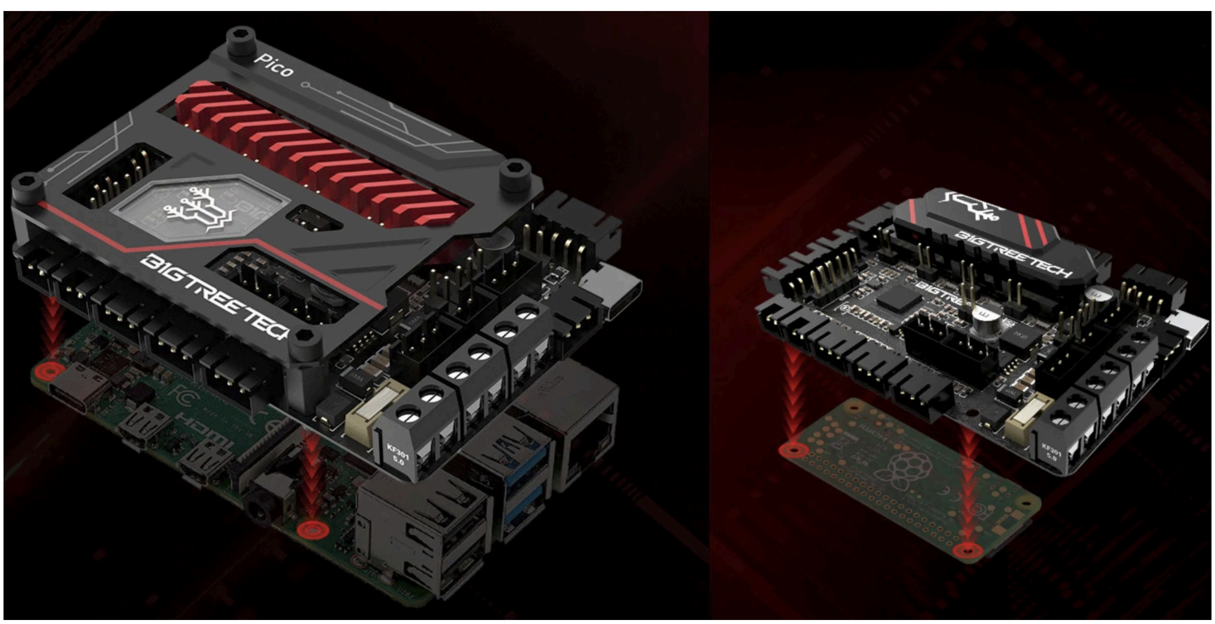



Figure 18: (Left): SKR Pico and Raspberry Pi 3 / 4, (Right): SKR Pico and Raspberry Pi 0 2W (Aufranc, 2022)

The decision to use the SKR pico over the Arduino came down to the fact that the Arduino and CNC shield must be vertically stacked, while the Raspberry Pi and SKR Pico can be placed in any orientation thanks to the included flexible connector shown below. Connections between the SKR pico and Raspberry Pi can be seen in Figure 19.

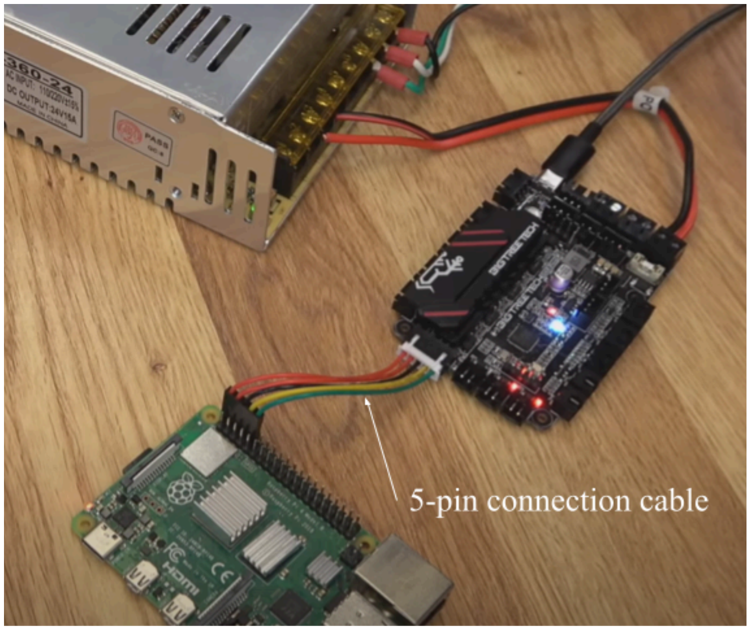



Figure 19: The flexible cable allows both boards to be attached flush with the base of the printer (Riley, 2022)

## 1.2.7: Software

Marlin and Klipper are the two most common types of softwares used to control 3D printers. Klipper is an open source software that is very customizable and will allow for full control over the printer. Since Klipper uses a Raspberry Pi for its computing power, it is fast and precise in comparison to Marlin.

## 1.2.8: Limit Switch

Limit switches are electronic components that provide reference points for an axis. This reference point can be programmed into the software of the printer and transferred to the microcontroller through a wired connection. Limit switches typically are programmed to have a certain component reach a start and end point of an axis. Customization of these points through software allows for parts that move axially to extrude within the desired print area and avoid collisions with other parts or mechanisms. Limit switches are shown in Figure 20 below.

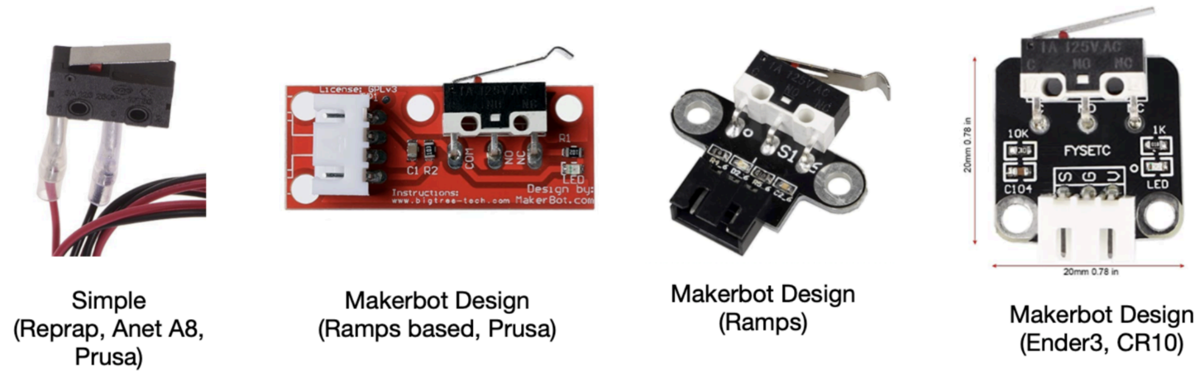



Figure 20: Common Types of Limit Switches used in 3D Printing (Reprap, 2021)

Limit Switches can be wired in two ways: NO (Normally Open) and NC (Normally Closed). In a Normally Open (NO) configuration, pressing the switch allows voltage to pass through and complete the circuit; In a Normally Closed (NC) setup, the switch has voltage constantly flowing through it, but interrupts the flow and stops the voltage when the switch is pressed (Reprap, 2021).

## 1.3: 3D Printer Coordinate Configurations

## 1.3.1: Cartesian Coordinates

Cartesian coordinate systems are the most common configuration of 3D printers. They use the coordinates X, Y, and Z to denote the 3 dimensional directions.

### CoreXY and H-Bot

Printers with CoreXY coordinate configuration use two motors to drive the print bed and one motor to drive the extruder. This configuration sees the motors drive the belts for the print bed in the X and Y directions, and the extruder in the Z direction. The kinematic graph of the belt and pulleys of the CoreXY printer is detailed in Figure 21 below.

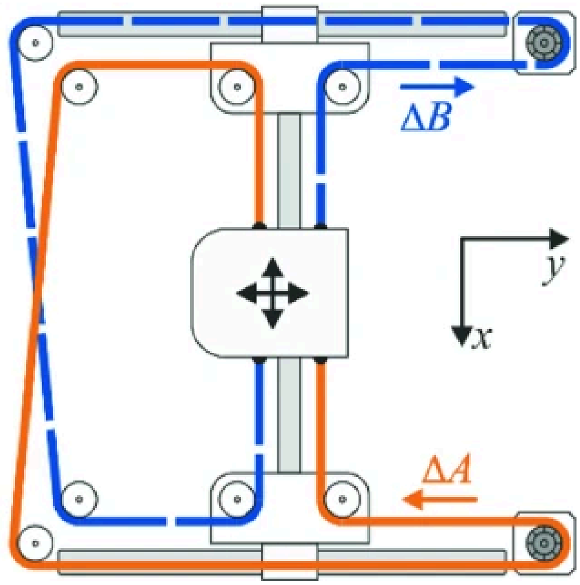


Figure 21: Belt and Pulley Configuration of a CoreXY Printer (Avdeev, Shvets, & Torubarov, 2020)

Advantages of CoreXY printers include increased precision and print speed due to the high number of motors and belt and pulley arrangement, reduced vibrations on the print bed, and a compacted design. The main flaws arise from poor belt tensioning. For accurate printing, the belts need even tension distribution and limited friction from the pulleys and motors. For some manufacturers, this can be a difficulty, but the coordinate system has been recently standardized to include proper tensioning devices and adequate electronics and motors. This has made it popular amongst 3D printer companies such as Ender, Ultimaker, and Markforged (Avdeev, Shvets, & Torubarov, 2020).

H-Bot printers, the XY plane's movement is carried out by a single belt in an H shape. As detailed Figure 22 below, these belts are driven using two motors that are parallel within the H shape.

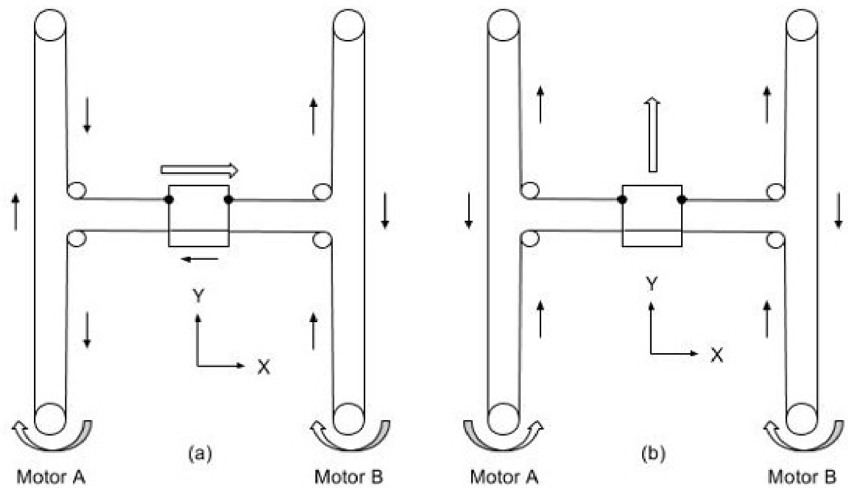



Figure 22: Belt and Pulley Configuration of an H-bot Printer (Avdeev, Shvets, & Torubarov, 2020)

H-Bot systems are simpler coordinate configurations in terms of belt tensioning and alignment whilst using less parts compared to CoreXY. CoreXY; however, does not have issues with asymmetric loading. H-Bot's belt configuration sees an uneven torque on the carriage, causing racking. CoreXY's overall longevity with symmetric loading sees it overtake H-Bot systems in terms of usage, as there are less concerns over inaccuracies or print failures (Avdeev & Torubarov, 2020). Both H-Bot and CoreXY feature the same motor movement, as described in the table below.

**Table 1: Motor Movement Pattern of the CoreXY and H-Bot Coordinate Systems**

| | |
|---|---|
| Both Motors Move Clockwise | Carriage Moves Left |
| Both Motors Move Counter Clockwise | Carriage Moves Right |
| Both Motors Move Opposite of Each Other | Carriage Moves Toward & Away |
| One Motor Moves | Carriage Moves Diagonal |

## CoreXZ

CoreXZ printers have the extruder moving in two directions, and the print bed moving in one direction. An example of this printer can be seen in Figure 23 below.

Figure 23: CoreXZ Printer Example (Prusa, 2024)

The extruder will move in the X-direction (left and right), and in the Z-direction (up and down). The print bed will only move in the Y-direction (back and forth). CoreXZ printers are cheap to make, have easy maintenance, and are usually accurate. This coordinate system; however, can be dimensionally inaccurate, as one of the motors has to move rather than being stationary (O'Connell, 2023).

## Belt

Belt printers are configured similarly to CoreXZ printers in terms of motor usage, but the print surface is a rotating belt. The extruder is at an angle and moves in the X and Z directions, while the belt moves in the Y direction. Advantages to this configuration include multiple prints without interruption, infinite print lengths, and the removal of build plate cleaning. Through infinite print lengths, belt printers can print objects such as swords, large trays, or any oblong object. This capability can be seen in Figure 24 below.

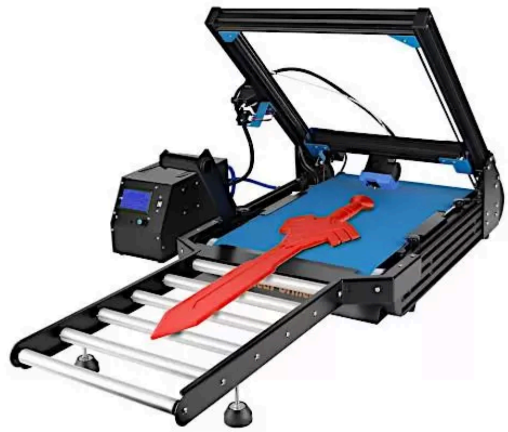


Figure 24: Belt Printer Printing a Sword (3DWithUs, 2024)

The main issues arise from the angled position of the extruder causing uneven overhangs (or sloped surfaces). As seen in Figure 25 below, an acceptable overhang is 45 degrees with the extruder vertically aligned.

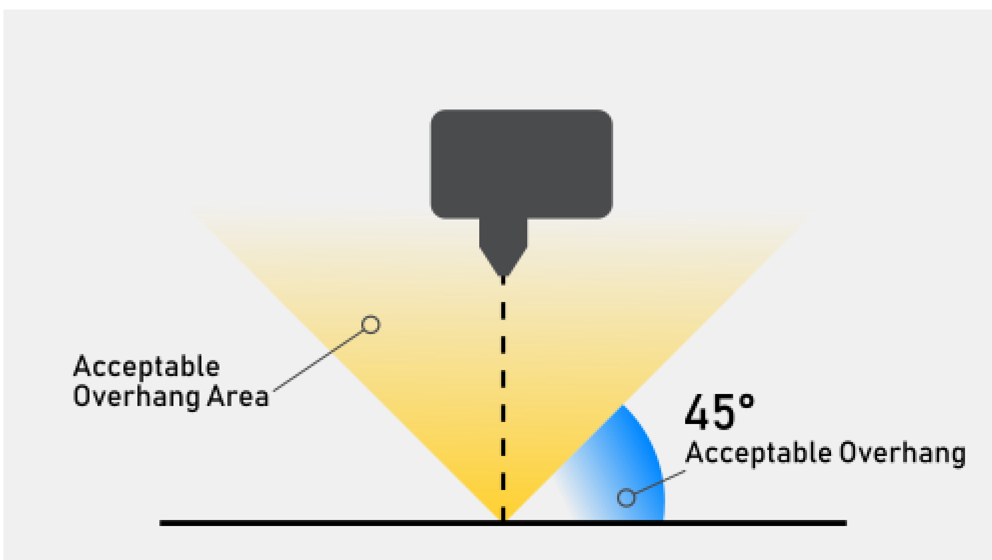



Figure 25: Acceptable Overhang Area for Vertically Aligned Extruders (Fasnacht, 2019)

Figure 26 below demonstrates that when the extruder is angled, the acceptable overhang rotates with the angle of a layer.

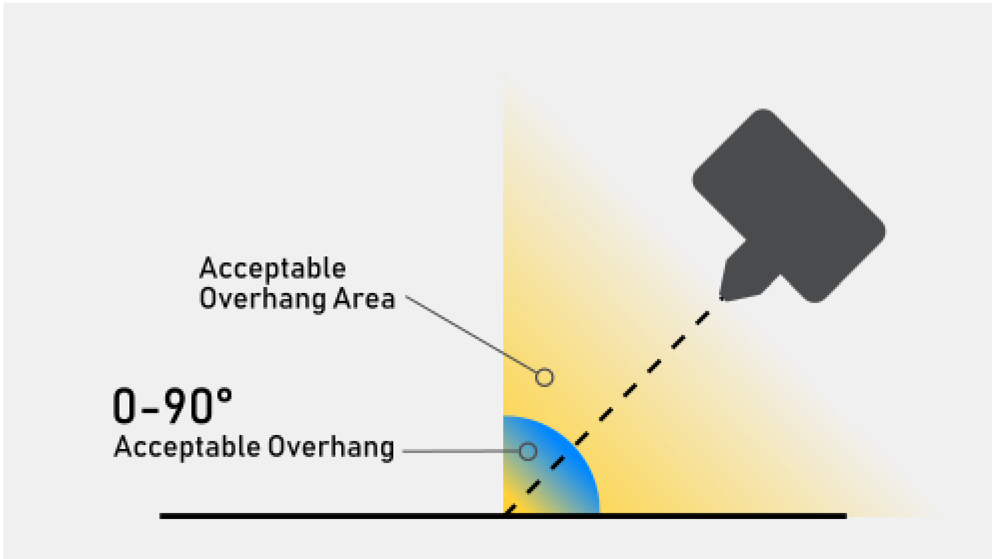



Figure 26: Acceptable Overhang Area for Angled Extruders (Fasnacht, 2019)

With belt printers, all of the features at the front of the printer become an overhang as seen in Figure 27 below. This is due to the print beginning from the front side of the part.

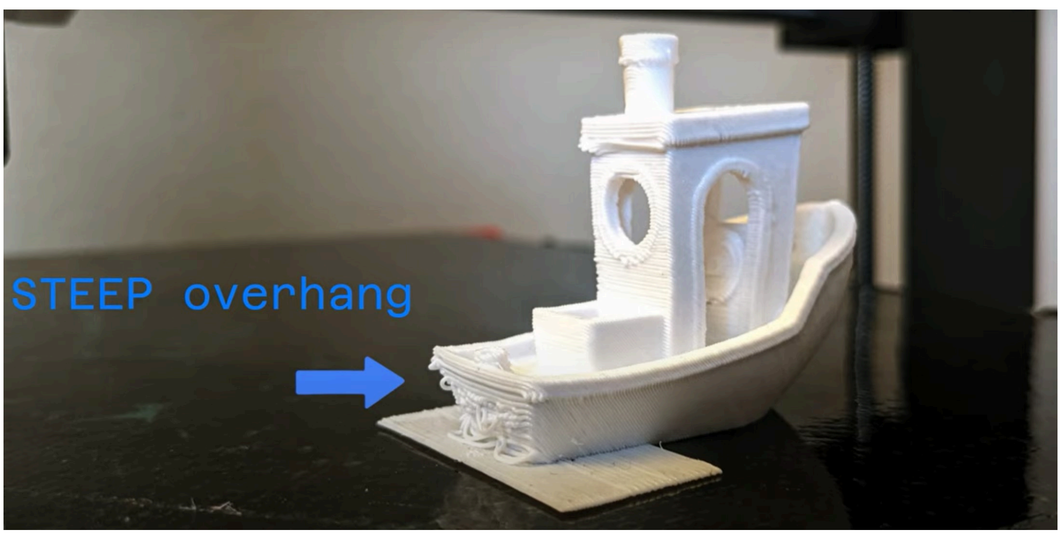



Figure 27: Front Overhang Caused by the Angled Extruder of a Belt Printer (O'Connell, 2023)

The features in the back of the print are all self supported and can be extruded in mid air. This extrusion angle also affects the strength of the material, particularly for thinner components. An example would be a thin, flat facing rectangle. A printer with a more standardized extruder orientation would only require a few layers, as it is printing from the bottom up. On a belt printer, that same rectangle would require many more layers as it goes from the back of the printer to the front, thus changing the strength of the part (O'Connell, 2023).

## SCARA

Selective Compliance Assembly Robotics Arm (SCARA) is a printer assembly consisting of an arm with two links attached to a vertical Z-axis joint. The two links are attached end to end, with each link having a circular movement. The extruder is attached to the end of the second link, and as a result of the geometry, a SCARA printer can print within a circular range of the main joint. A SCARA robot can be seen in Figure 28 below. Common alternatives are having two main joints and four links, meaning the need for a motor between the links is not necessary, due to the machine acting as a five-bar mechanism.

Advantages include being relatively inexpensive and taking up less space. Since there are no belts and few motors, the total cost of the printer is low. In addition to the low number of parts, the printer design takes up less space than traditional CoreXY printers.

Disadvantages include difficulties in calibration and precision. Since the second link's position is dependent on the angle of the first link, any error in the first link will only magnify the error in position of the extruder. In addition, because not many printers use SCARA, there are limited resources for using non-cartesian coordinates. Either polar coordinates or the use of DH parameters would be required for calculating the extruder (All3DP, 2021).

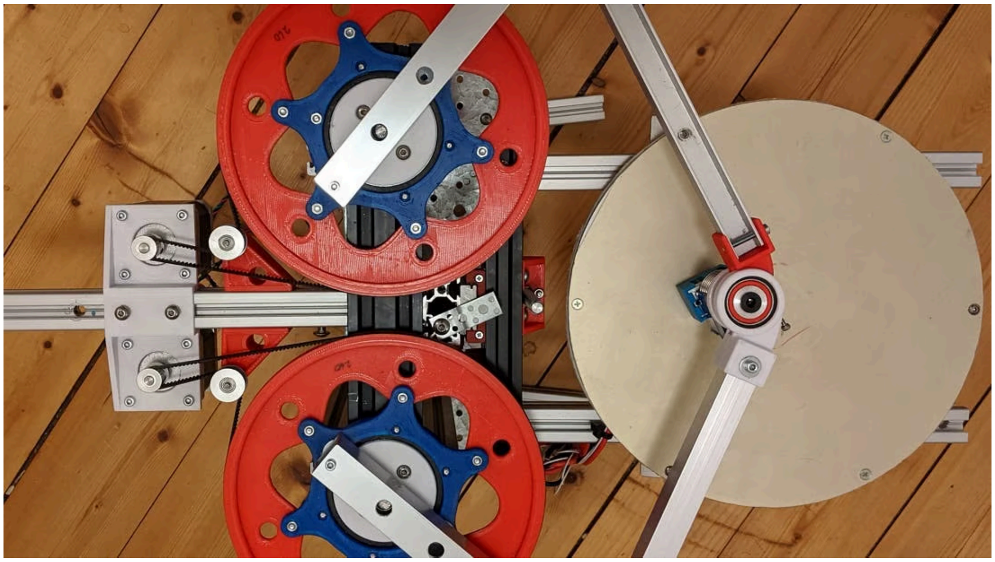


Figure 28. An example of a 5-bar SCARA printer (O'Connell, 2021)

## Delta

Unlike the standard configuration of the print bed and extruder moving in the X, Y, and Z axes, Delta printers move the extruder in all three directions. Delta printers achieve movement through a stationary, circular print bed and a triangular linkage system for the extruder to freely move. This movement compared to the standard cartesian system is signified by Figure 29 below.

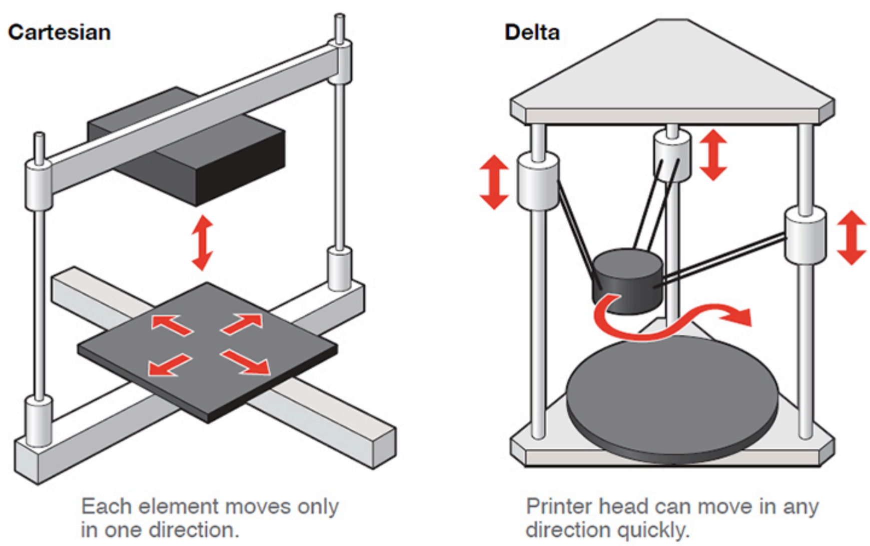



Figure 29: Difference of Extrusion Between Standard Cartesian and Delta Printers (O'Connell, 2023)

With the triangular linkage system, Delta printers extrude at extremely high speeds, with some extruding at 300 millimeters per second. These speeds make Delta printers ideal for multiple small components. For larger prints, limitations come from the print bed size. The circular print bed is typically smaller, with the height using a majority of the space. For larger parts, this limits the printing to taller parts that do not use a majority of the print bed's diameter. Components that encompass more space in terms of width would be better suited for a large standard cartesian printer. Another downside is the software setup and troubleshooting. Most Delta printers do not come prebuilt. This allows for flaws with print quality if the user is not knowledgeable in building 3D printers. Due to lack of mass adoption, troubleshooting the printer can also be more difficult. If a user has any trouble with the printer, there is a relatively small community to gain answers from (O'Connell, 2023).

## 1.3.2: Polar Coordinates

Polar coordinate printers are uncommon and not widely used in the industry. Unlike the cartesian coordinate printers, polar printers have a circular build plate. The "X-Y" coordinates for the polar printers are calculated with the length and angle from an origin point. As shown in Figure 30 below, 'r' is the length and $\theta$ is the angle. Together they are used to find a point relative to the origin.

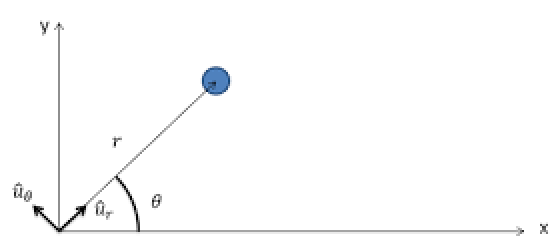



Figure 30: Example of Polar Coordinates (r is length and $\theta$ is the angle) (*The home of E3D,* n.d.).

With continuous increasing of the angle, it would eventually make a full circle, making our build plate. The Z-axis is the same as CoreXY printers that just go up and down with the extruder mounted to it. This Z-axis allows us to go from a 2-dimensional circle, to a

3-dimensional cylinder as our entire build-space. An example of a SCARA printer can be seen in Figure 31 below.


Figure 31: Example of Polar Printer (*The home of E3D,* n.d.)

# Chapter 2: Ideation/Methodology

## 2.1 Mind Map:

Mind maps are a visual representation of information organized in a hierarchical structure. Mind maps are formed from one or more large ideas at the center with several branches sprouting off of the center to represent smaller concepts. These smaller concepts all combine to make up the large concept, with each holding a different form of significance to the main system (MindMapping.com, NDA). We have the large concept of the Palm Print and the smaller concepts that comprise of the components, software, and kinematic schemes required to produce a handheld 3D printer. The software, hardware, and kinematics functions in 3D printing were discussed in Chapter 1. The mind map assisted the team to determine what needed to be purchased, as well as a systems engineering perspective to ensure harmony between each component. The Palm Print mind map can be seen in Figure 32 below.

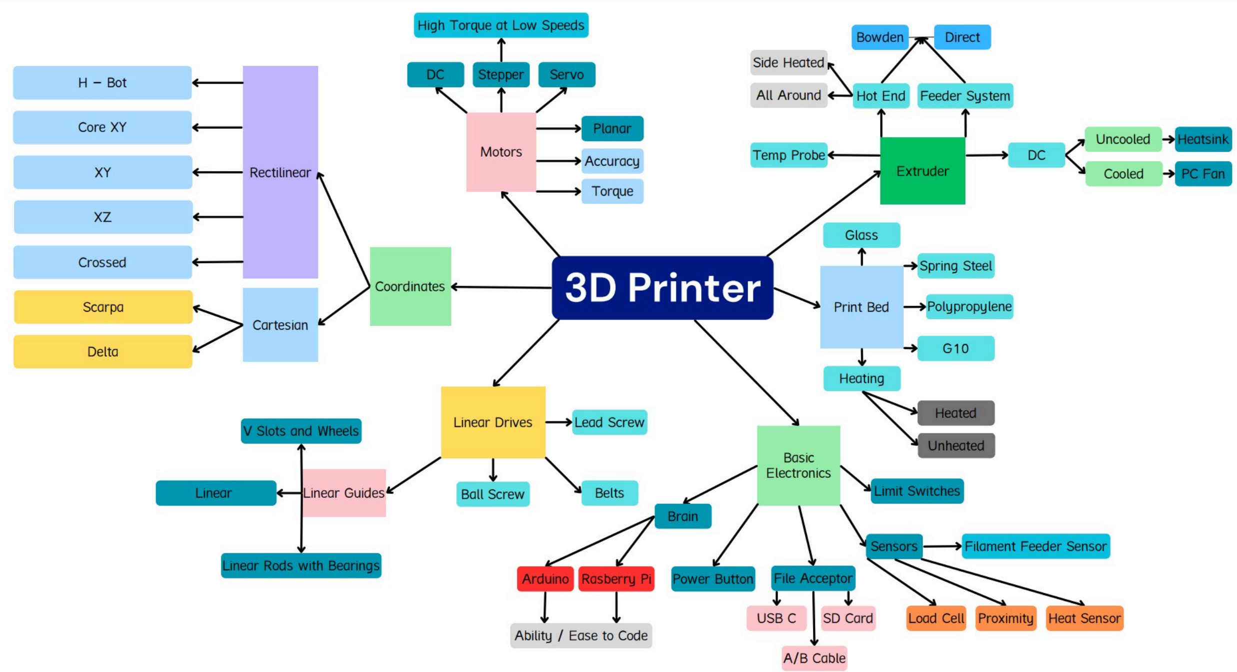



Figure 32: Mind Map of the Palm Print System and Individual Components

## 2.2 Pugh Matrices:

The Pugh Matrix is a matrix that takes numerous design concepts or components and assigns criteria-based weights to determine the best option for the engineer (American Society of Quality, NDA). The team decided to use this matrix format to assess the best forms of various components and coordinate systems based on their pros and cons.

### 2.2.1 Extruder Pugh Matrix:

| *1=bad, 5=good* | Size | Weight | Cost | Foldability | Assembly | Servicability | Structural Stability | Total |
|---|---|---|---|---|---|---|---|---|
| *Category weights* | 5 | 4 | 2 | 3 | 2 | 1 | 2 | |
| **Bowden** | 5 | 4 | 4 | 4 | 3 | 4 | 4 | |
| *Bowden - weighted scores* | 25 | 16 | 8 | 12 | 6 | 4 | 8 | 79 |
| **Direct** | 2 | 3 | 3 | 2 | 4 | 3 | 4 | |
| *Direct - weighted scores* | 10 | 12 | 6 | 6 | 8 | 3 | 8 | 53 |

Figure 33: Extruder Pugh Matrix

The first component explored, as seen in Figure 33 above, was the extruder. The extruders evaluated were the Bowden and Direct extruders. The largest category weights were given to the size and weight of the extruder due to the dimensions our team wanted from the

Palm Print. A larger, heavier extruder would result in increased difficulty for transportation. The benefits from the added bulk were also assessed to not have any impact on the structural stability, as both extruders are able to withstand the problems experienced from high temperatures. The team determined that Bowden extruders not only met the main criteria of a small, lightweight frame, but were also cheaper, and easier to incorporate into any folding mechanism.

### 2.2.2 Feeder Motor Pugh Matrix:

Through the feeder motor Pugh Matrix, the team looked to determine the best motor to move polylactic acid (PLA) filament to the extruder. As seen in Figure 34 below, the primary weights were assigned to size, position control, reliability, and torque.

| *1=bad, 5=good* | Size | Position Control | Cost | Reliability | Torque | Noise | Efficiency | Speed Control | Total: | Rank: |
|---|---|---|---|---|---|---|---|---|---|---|
| *Category Weights* | 5 | 5 | 3 | 5 | 5 | 2 | 3 | 4 | - | - |
| **Stepper Motor** | 4 | **5** | 4 | **5** | 4 | 2 | 2 | 4 | | |
| *Stepper Weighted Score* | 20 | 25 | 12 | 25 | 20 | 4 | 6 | 16 | 128 | 1 |
| **DC Motor** | 4 | 1 | **5** | 1 | 2 | **4.5** | **4.5** | 3 | | |
| *DC Weighted Score* | 20 | 5 | 15 | 5 | 10 | 9 | 13.5 | 12 | 89.5 | 3 |
| **Servo Motor** | **4.5** | 2 | 2 | 3 | **5** | 3 | 3 | 5 | | |
| *Servo Weighted Score* | 22.5 | 10 | 6 | 15 | 25 | 6 | 9 | 20 | 113.5 | 2 |

Figure 34: Feeder Motor Pugh Matrix

The team wanted a smaller sized motor to fit within the smaller dimensions of the frame designed. This helps with spacing for the kinematic mechanism of the extruder section. Stepper motors produce high torques at low speeds whilst maintaining a smaller form factor. The smaller sized feeder motors are especially prevalent amongst the company NEMA. The feeder does not need the higher speeds of a servo motor to function properly. The DC motor was not chosen due to its poor positional control with the Klipper software interface, making it unreliable for feeding filament. It also does not have the high torques produced by stepper and servo motors. The main reason that the stepper motor was chosen over the servo motor was due to the higher cost of the servo motor. With a primary goal being reduced cost, the team deemed it necessary to move forward with the stepper motor.

### 2.2.3 Coordinate System Pugh Matrix:

In the coordinate system Pugh Matrix, seven coordinate systems were analyzed to determine a kinematic scheme that would reliably move the print bed and extruder, fit into a compact frame, and interface with a folding mechanism. As seen in Figure 35 below, sizing, position control, reliability, and foldability were the primary criteria desired by the team.

| zz | Overall Size | Position Control | Cost | Reliability | Ease to Program | Max Print size | Ease of Design + Assembly | Foldability | Maintenance / Accessibility | Total: | Rank: |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Category Weights* | 5 | 5 | 3 | 5 | 3 | 2 | 3 | 4 | 2 | - | - |
| **Core XY** | 4 | **4.5** | **4** | **4.5** | **4** | 3 | 4 | **4.5** | 3 | | |
| *Core XY Weighted Score* | 20 | 22.5 | 12 | 22.5 | 12 | 6 | 12 | 18 | 6 | 131 | 1 |
| **H-Bot** | 3.5 | **4.5** | **4** | 4 | **4** | 3 | **4.5** | **4.5** | 3.5 | | |
| *H-Bot Weighted Score* | 17.5 | 22.5 | 12 | 20 | 12 | 6 | 13.5 | 18 | 7 | 128.5 | 2 |
| **Belt** | 2 | 1 | 1 | 1 | 1 | 4 | 2.5 | 1 | 2 | | |
| *Belt Weighted Score* | 10 | 5 | 3 | 5 | 3 | 8 | 7.5 | 4 | 4 | 49.5 | 6 |
| **Core XZ** | 3 | 3 | 3.5 | 3 | 2 | **5** | 3.5 | 2.5 | **4** | | |
| *Core XZ Weighted Score* | 15 | 15 | 10.5 | 15 | 6 | 10 | 10.5 | 10 | 8 | 100 | 3 |
| **Delta** | 2 | 1 | 2 | 1 | 1 | 3 | 1.5 | 1 | 2 | | |
| *Delta Weighted Score* | 10 | 5 | 6 | 5 | 3 | 6 | 4.5 | 4 | 4 | 47.5 | 7 |
| **Scara** | **5** | 1 | 3 | 1 | 1 | 3.5 | 1.5 | 5 | 2 | | |
| *Scara Weighted Score* | 25 | 5 | 9 | 5 | 3 | 7 | 4.5 | 20 | 4 | 82.5 | 5 |
| **Polar** | 4.5 | 2 | **4** | 3 | 2 | 3 | 4 | 2.5 | 3 | | |
| *Polar Weighted Score* | 22.5 | 10 | 12 | 15 | 6 | 6 | 12 | 10 | 6 | 99.5 | 4 |

Figure 35: Coordinate System Pugh Matrix

The CoreXY coordinate system was most desired since it matched the sizing and folding criteria better than the other systems, and it also is used in numerous commercial printers. These printers are able to reliably print thousands of designs, and are easier to control the movement through G-code. The pricing of the system was also among the cheapest, as it only requires three motors.

The H-Bot coordinate system was not chosen due to the reliability and position control. The H-Bot coordinate system has troubles with constant usage of the belts and pulleys. H-Bot mechanisms, which use one less motor, have less balanced drive forces, resulting in racking in the gantry of the system. The belt tensioning must be tighter and are not as easy to execute motion when compared to the square driving mechanism of the CoreXY.

While printers with polar coordinates are small, the mechanical controls and software are not easy to produce compared to the cartesian printers. Most software packages, Klipper included, are better integrated for cartesian coordinate systems. This means that the reliability of getting quality prints is lower due to the higher chance of software bugs.

Belt and Delta printing were not feasible for the team due to the large size required for each system, as well as their complications with software implementation. The conveyor belt of the Belt printer leads to a large print area needed, and the triangular linkage system required in delta printers has a large vertical structure for support. Compacting both of these printers would lead to printing complications, as these systems use specialized mechanisms for extrusion and movement that are too large to physically shrink into a handheld assembly. The cost of these systems would also be amongst the highest due to the greater number of material and motors required. Software integration is also not widely supported for these printers due to their niche status. Inevitably, this can cause troubleshooting errors that the other coordinate systems do not face (O'Connell, J., 2023).

### 2.2.4 Print Bed Material Pugh Matrix:

To determine the type of material used for the print bed, the team evaluated 4 different kinds of reliable print bed materials in 7 different parameters. As seen in Figure 36 below, G10 was the best material based on the 7 parameters. While G10 was the best, the team decided to choose glass.

| *1=bad, 5=good* | Cost | Weight | Flexibility | Durability | Heated? | Adhesion w/out heat | Adhesion with heat | Total |
|---|---|---|---|---|---|---|---|---|
| *Category weights* | 4 | 5 | 2 | 3 | 1 | 3 | 1 | |
| **Glass** | 3 | 2 | 1 | 5 | 4 | 3 | 4 | |
| *Glass - weighted scores* | 12 | 10 | 2 | 15 | 4 | 9 | 4 | 56 |
| **Spring Steel PEI** | 1.5 | 2 | 5 | 4 | 4 | 3 | 4 | |
| *Spring Steel - weighted scores* | 6 | 10 | 10 | 12 | 4 | 9 | 4 | 55 |
| **G10** | 4 | 4 | 2 | 3 | 2 | 1 | 3 | |
| *G10 - weighted scores* | 16 | 20 | 4 | 9 | 2 | 3 | 3 | 57 |
| **Polypropalene** | 3 | 4 | 3 | 2 | 1 | 2 | 3 | |
| *Polypropalene - weighted scores* | 12 | 20 | 6 | 6 | 1 | 6 | 3 | 54 |

***Note: this is for FDM printing with PLA only, these scores would vary for other filament materials

Figure 36: Print Bed Material Pugh Matrix

The team chose to use glass due to its relatively cheap cost, and proven effectiveness with printing PLA on other printers on the market. It is a popular material choice since it can handle repetitive heating and cooling. It is also known to have effective material adhesion, even without being heated, which is important as the Palm Print's print bed will not be heated.

Spring steel is also popular among other printers and has been proven to stand up to the tests of repetitive printing. The most appealing part of sprint steel is its flexibility and easy removal from the gantry. This is achieved by the bottom side of the spring steel being magnetic. Because the team was not going to attach it magnetically, it was determined to be an unworthy purchase for an increased cost.

G10, which shares numerous similarities to glass, earned a higher score in the matrix. It earned a better score in cost, weight and flexibility. However, due to its lower durability and adhesion, the team decided glass was the better option. Over time, after being repeatedly heated and cooled, G10 has shown signs of warping. This causes the print surface to no longer be level, severely reducing the ability to print.

Polypropylene saw the worst results amongst the other materials. While it is relatively cheap, and has good adhesion due to plastics bonding with each other better, this was not enough to convince the team to use it. It has also shown problems with warping after continuous printing and is easily scratchable, causing problems with adhesion.

## 2.2.5: Linear Drive Mechanism Pugh Matrix for X and Y Axes:

The linear drive mechanism Pugh Matrix, shown in Figure 37 below, uses 9 different categories to weigh 3 different mechanisms for linear movement. This Pugh Matrix prioritizes precision, torque and collapsibility as the most desirable categories. High precision is one of the most important traits for any usable 3D printer. The precision of an extruder's location is the difference between a failed print, a good print, and a perfect print. Torque is also a highly desirable trait as without enough of it the printer will not be able to move the bed or extruder to the desired coordinates. The torque must also be strong enough to move the bed while a full print is attached. Collapsibility was also chosen as a most desirable trait, as creating a collapsible printer was one of the main goals of Palm Print.

| *1=bad, 5=good* | Cost 5=low | Weight 5=low | Precision 5=good | Torque required 5=high | Speed 5=fast | Maintenance 5=low | High Load | Continuous High speed | Collapsibility | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| *Category weights* | 3 | 4 | 5 | 5 | 3 | 2 | 2.5 | 4 | 5 | |
| **Lead Screw** | 2.5 | 1 | 4 | 1 | 1.5 | 4 | 5 | 2 | 1 | |
| *Lead Screw - weighted scores* | 7.5 | 4 | 20 | 5 | 4.5 | 8 | 12.5 | 8 | 5 | 74.5 |
| **Belts** | 5 | 5 | 3.5 | 4 | 5 | 2.5 | 2.5 | 5 | 4 | |
| *Belts - weighted scores* | 15 | 20 | 17.5 | 20 | 15 | 5 | 6.25 | 20 | 20 | 138.75 |
| **Ball Screw** | 1 | 2 | 5 | 2 | 5 | 4 | 5 | 4 | 1 | |
| *Ball Screw - weighted scores* | 3 | 8 | 25 | 10 | 15 | 8 | 12.5 | 16 | 5 | 102.5 |

Figure 37: Linear Drive for X and Y-Axes Pugh Matrix

After ranking the desired characteristics and assigning a value for each linear drive method, the team chose to use belts and pulleys as the linear drive method of the X and Y axes. Belts offered a high acceleration, were lightweight and easy to secure, while also being cost effective. Lead screws are better suited for slow applications, and degrade more quickly at continuous high speeds. Ball screws would have performed well, however for this application they would have been excessive as well as costly. Both ball screws and lead screws took up more space and would have been harder to mount.

## 2.2.6: Drive Motor Pugh Matrix:

The drive motor Pugh Matrix prioritized high precision, torque, and weight due to the motors being integral to the movement of the belts along the pulleys. In order to comply with the G-code, the motor must have high precision to produce a print with correct layer positioning. Any offset in the layer position could result in distortion of the design. As shown in Figure 38 below, we selected the stepper motor for this project.

| *1=bad, 5=good* | Cost 5=low | Weight 5=low | Precision 5=good | High torque output 5=high | Speed 5=fast | Maintenance 5=low | Total |
|---|---|---|---|---|---|---|---|
| *Category weights* | 2 | 3.5 | 5 | 3.5 | 2 | 2 | |
| **Stepper Motor** | 2 | 2 | 5 | 5 | 2 | 4 | |
| *Stepper Motor - weighted scores* | 4 | 7 | 25 | 17.5 | 4 | 8 | 65.5 |
| **Servo Motor** | 3 | 4 | 5 | 2 | 2 | 4 | |
| *Servo Motor - weighted scores* | 6 | 14 | 25 | 7 | 4 | 8 | 64 |
| **DC Motor** | 4 | 4 | 1 | 2 | 5 | 2 | |
| *DC Motor - weighted scores* | 8 | 14 | 5 | 7 | 10 | 4 | 48 |

Figure 38: Drive Motor Pugh Matrix

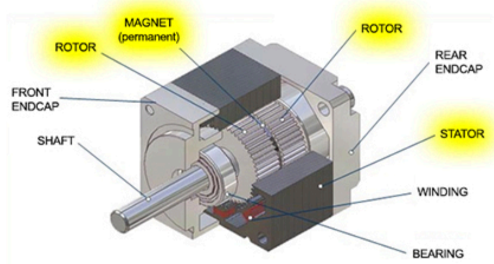



Figure 39: Stepper Motor Diagram (AMCI, 2024)

In the Pugh Matrix, the stepper motor emerged as the most optimal motor for belt and extruder movement. Stepper motors are favorable because of their ability to “provide precise positioning and control at low speeds" (Kohli, 2023).  A depiction of a stepper motor can be seen in Figure 39 above. Servo motors “are best suited for high-speed applications that involve dynamic load changes like robot arms, while stepper control systems are preferred for applications that require low-to-medium acceleration and high holding torque such as 3D printers and Conveyors (STXIM, 2021). Stepper motors are also cheaper than servo motors because they use less expensive magnets, rarely incorporate gearboxes, and due to their ability to generate holding torque, they consume less power at zero speed (AMCI, 2024)

## 2.3 Reverse Engineering:

Reverse Engineering is the process of deconstructing an assembly to extract information on how each component works within the system. Mechanical components, electronic hardware, and software structures can be subjected to Reverse Engineering (Lutkevich, B., NDA). The team used this method to disassemble different printing devices. The Mynt3D Pro printer pen and the previous Palm Print MQPs were all deconstructed and analyzed for a better understanding of printing mechanisms within smaller printing frames.

### 2.3.1 Printer Pen:

The Mynt3D pro is a pen that can produce drawable PLA extrusions. The team reverse-engineered this pen to examine the small-scale motor systems used, as well as the miniature extruder and hot-end system. Since the pen is designed for users to control where the plastic is extruded, the main motor is only responsible for pushing filament into the hot end. As seen in Figure 40 below, the kinematic system uses multiple gears for the direct drive extruder in order to shrink the process down. The motor used appears to be a DC motor, being more efficient than stepper motors at the cost of having less control over movement. The pen also uses a much smaller hot end for the extruder compared to full-size 3D printers, which is encased in an insulating material.

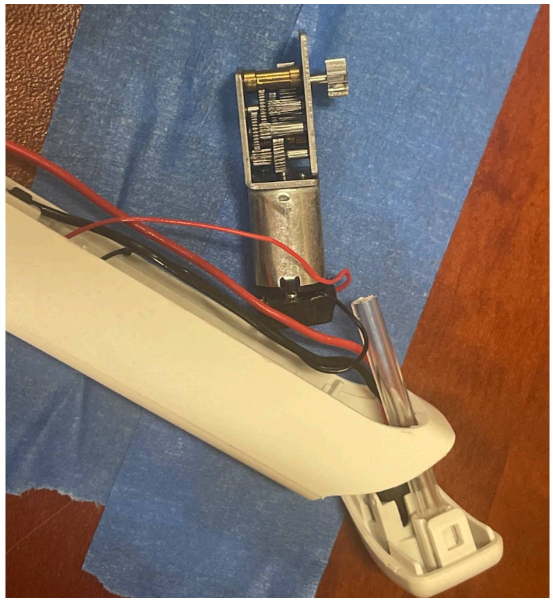


Figure 40: Reverse Engineering of the Mynt3D Pen. The figure shows the gearbox used for the direct drive extruder.

The team did not take many ideas from this small-scale design due to it not regarding printer accuracy. The filament feeding and movement processes work far too differently compared to a traditional coordinate system printer.

## 2.3.2: 2020-2021 Palm Print:

The 2020-2021 Palm Print is designed to have the extruder move in the X and Z-axes, whilst the print bed moves in the Y-Axis. This version of the Palm Print can be seen in Figure 41.

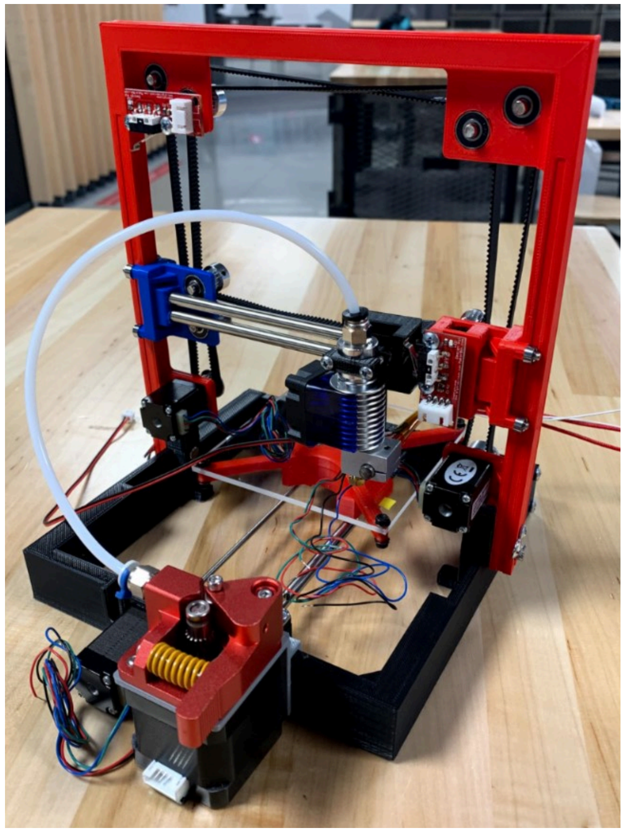


Figure 41: 2020-2021 Palm Print Assembly (Rementer, Wehbe, & Wilkinson, 2021)

The main points taken from the design were the folding mechanism being simple and easy to use, as well as sound structural support for the extruder. The design; however, was larger than what the team had envisioned, and the folding mechanism used a large amount of space for portability. The design helped the team explore the option of creating a printer with a similar kinematic scheme and folding mechanism, which is further discussed in Section 2.4., but components such as the print bed, extruder, and pulley mechanisms were too large in total height to extract inspiration beyond the ideation stage.

### 2.3.3: 2021-2022 Palm Print:

The 2021-2022 Palm Print used an H-Bot coordinate system to help minimize the scale of the printer. Key takeaways from the printer were its small size, detachable Z-Axis, and low quality motors. This version of the Palm Print was the smallest of all the cartesian based iterations. It used lead screws for the X and Y-Axis motion, but the team preferred the use of belts due to the reasons given in Section 2.2.5.

As seen in Figure 42 below, the removable Z-Axis used a slot mechanism for attachment and detachment.

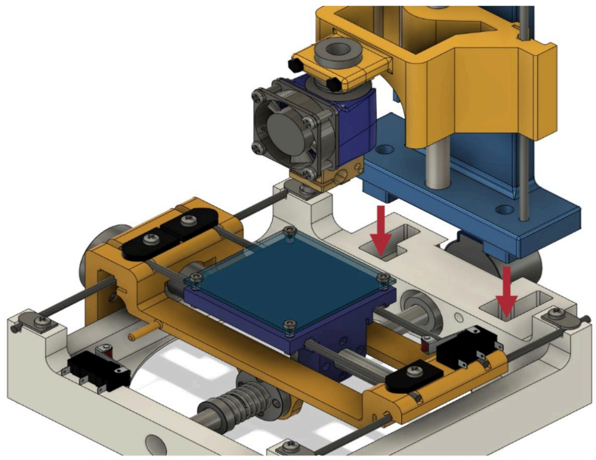


Figure 42: 2021-2022 Palm Print CAD and Detachable Z-Axis (De Moraes, Gonzalez Garcia, Morin, & Navarro Aguayo, 2022)

The idea was considered by the team; however, a folding mechanism was determined to be better suited for travel with a specialized case. One point made by the 2021-2022 Palm Print team was their low quality motors. The NEMA 14 motors did not provide enough torque for the system to reliably move. The lower budget of the team can be attributed to this. This indicated to the team to look into motors with higher torque, as the budget for this year's Palm Print is significantly higher.

### 2.3.4 2022-2023 Palm Print:

The 2022-2023 Palm Print was unique since it was the only iteration of the Palm Print to feature polar coordinates. This coordinate system allowed for a smaller print bed, which helped produce a smaller print frame. As mentioned in Section 2.2.3, the team was not in favor of using polar coordinates due to the lack of reliability of multiple prints, as well as the coordinate system not being supported as well as cartesian coordinates for software.

The size of the extruder and the motors were the team's favorite aspect of the design, as the components were the smallest seen throughout the MQPs. The team liked the motor holder of the Z-axis assembly, as well as the lead screw system. The Z-axis frame can be seen in the figure below. The Z-axis folding mechanism that used a screw detachment was also viewed favorably, and was effective in folding flat and away from the print bed. The folded Z-axis frame can be seen in Figure 43 below.

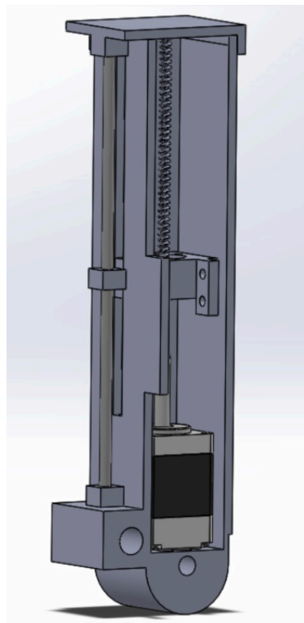


Figure 43: CAD of the 2022-2023 Palm Print Z Axis Frame (Doan, Duval, Murguia, & Wekerle, 2023)

The extruder held by a cantilever was explored for future designs by the team; however, we wanted to make improvements on the stability. The cantilever was connected by two screws and not straightly aligned, as it was weighed down by the extruder. This could also lead to poor print quality, as the cantilever could shift upwards when touching the print bed. This year's Palm Print was inspired by the design's foldability potential. With the cantilever design, the extruder in its folded state would not interfere with the base. Improvements made this year from the 2022-2023 Palm Print can be seen in Section 3.1.

## 2.4 Folding Mechanism Sketches:

To brainstorm designs for the Palm Print, the team created sketches for the folding mechanisms. These sketches were done before creating Computer Aided Design (CAD) models of the Palm Print, and brought the team closer to the prototyping stage. The folding mechanism is required to ensure transportability, whilst satisfying the chosen coordinate system, print area, and surrounding dimensions. Below, Figure 44 shows the first sketch of a hinged folding mechanism that collapses a full 90 degrees into a slotted area for the extruder to rest. This is meant for a CoreXY system.

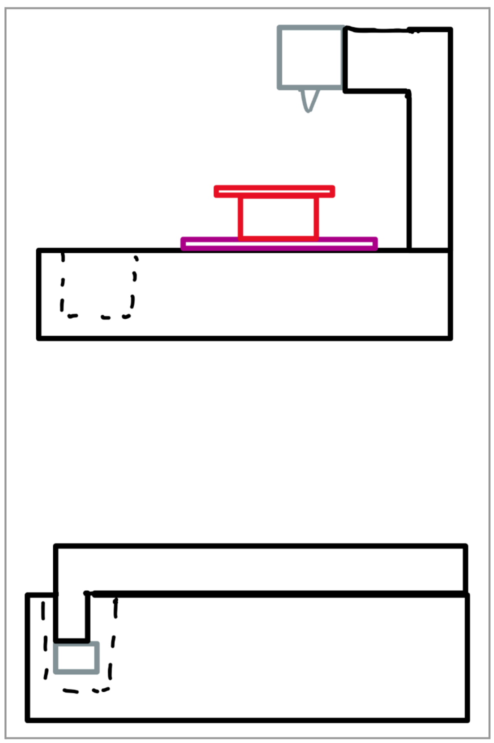


Figure 44: 90 Degree Fold Forward into a Slot for the Extruder

This folding mechanism was not chosen due to the inability to fully collapse the Z-Axis system without interfering with the X and Y coordinates, particularly the print bed. The slot was also a concern, as there would have to be a major increase in the length of the printer base to provide a slot section.

The second sketch, as seen in Figure 45, details the same mechanism as the first sketch; however, the hinge does not collapse 90 degrees, but rather 45-60 degrees.

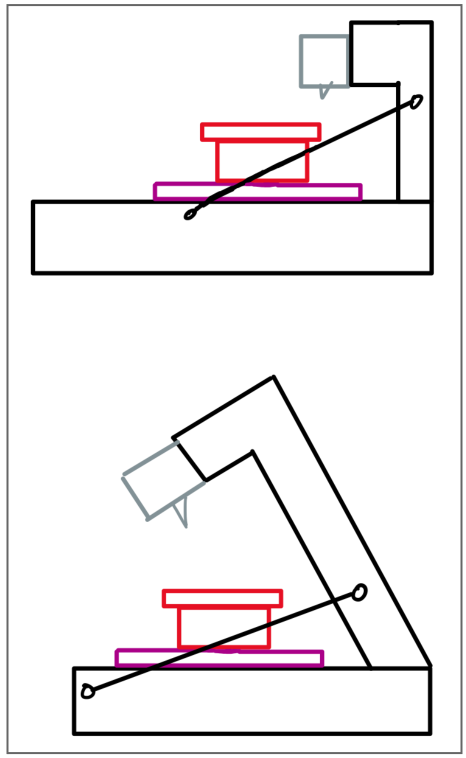


Figure 45: Hinge Mechanism that Folds the Z-Axis 45-60 Degrees

The team did not progress with this folding mechanism due to the added bulk to the Z-axis required in attaching a hinge mechanism to the system. To have a hinge, the width of the Z-axis would need to be equal to, or approximate to the sides of the base.

An idea for a potential CoreXZ printer was discussed after conducting the reverse engineering of the 2020-2021 Palm Print in Section 2.3.2. We discussed how to make that design smaller, and if the design had the ability to take less space than CoreXY designs. This CoreXZ design would have used the “handlebar” hinge mechanism with the section for the X and Z axes folding over the entire print bed movement system. The circle sketch for this concept can be seen in Figure 46 below.

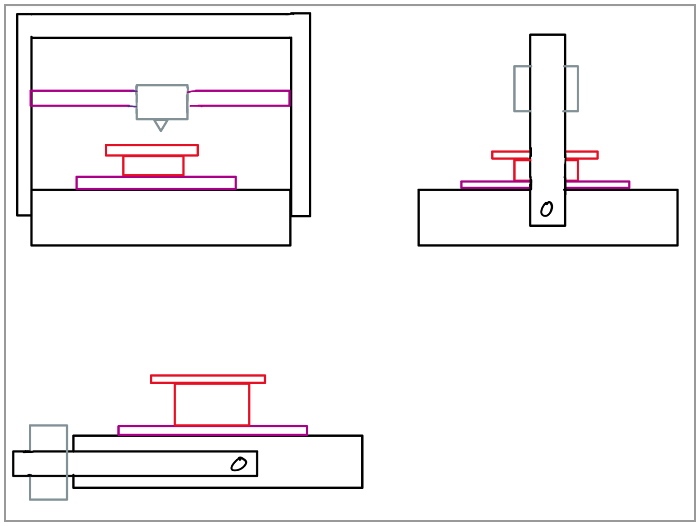


Figure 46: CoreXZ “Handlebar” Folding Method

The next sketch shows a concept similar to the 2022-2023 Palm Print, explained in Section 2.3.4. This folding mechanism sees the Z-axis locked in place to the frame, and then unlocked to fold flat, which can be seen in Figure 47 below.

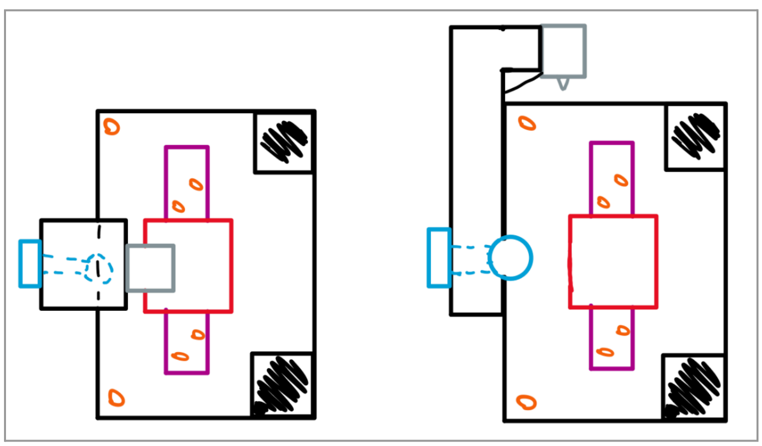


Figure 47: CoreXY Lock and Fold Method

This sketch was the folding mechanism the team opted for; however, the team wanted to use a method that differed from the method of using a screw. The reasons for this change was to improve the ease of use for the user and remove the need of an external tool such as a screwdriver. Section 3.1.3 showcases the design and hardware involved in the folding mechanism adopted by the team.

# Chapter 3: CAD and Mechanical Prototypes

The team created three prototypes of the X-Y axes and one Z-axis prototype. The X-Y versions all use the same linear drives, belts and pulleys, with the difference being the linear guide mechanisms. Each prototype was designed using Autodesk Fusion 360, a cloud based CAD program that allowed the team to actively work on each design seamlessly and concurrently. Once each CAD design was completed, the team assembled hardware prototypes.

## 3.1: Z Motion

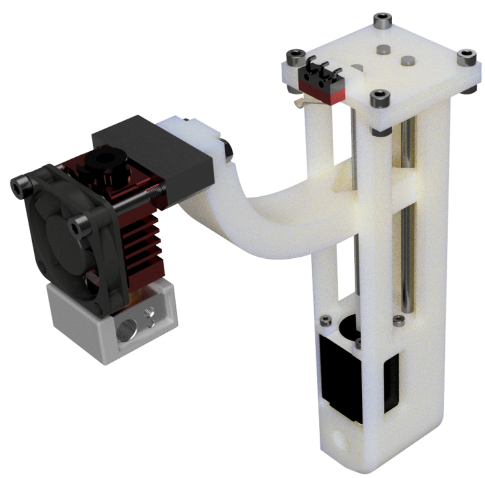


Figure 48: Fusion 360 Render of the Z-Axis

The Z-axis moves the extruder in all vertical directions for its full range of motion. The main driving force of the component is the lead screw attached to a NEMA 8 motor. The lead screw is attached to an anti-backlash nut, which is attached to a cantilever supporting the extruder. As part of our design requirements, the Z-axis must be able to be folded down for easier carrying, so an eccentric cam is responsible for locking the Z-axis to the frame in its engaged position, while also allowing users to fold the axis away or remove it entirely. The Z-axis assembly can be seen in Figure 48 above.

### 3.1.1: Motor and Lead Screw

The lead screw is attached to the motor, the NEMA 8 stepper motor, either directly or with a coupling.. Attached to the lead screw is an anti-backlash nut, which converts the rotational motion of the motor to translational motion of the cantilever arm along the lead screw's central axis.

As the motor turns the lead screw, the cantilever and anti-backlash nut naturally turns horizontally with the screw, rather than moving vertically. To counteract this, vertical rods are placed through the cantilever to prevent the cantilever from rotating horizontally. The rods are in contact with the inside of the cantilever and polyoxymethylene (POM, or "Delrin") chips. The purpose of the Delrin chips is to provide a smooth, low friction contact surface while also applying light pressure against the vertical guide rods to keep the cantilever from rotating. A picture of the Delrin chips and the inside of the cantilever are shown in Figure 49 below.

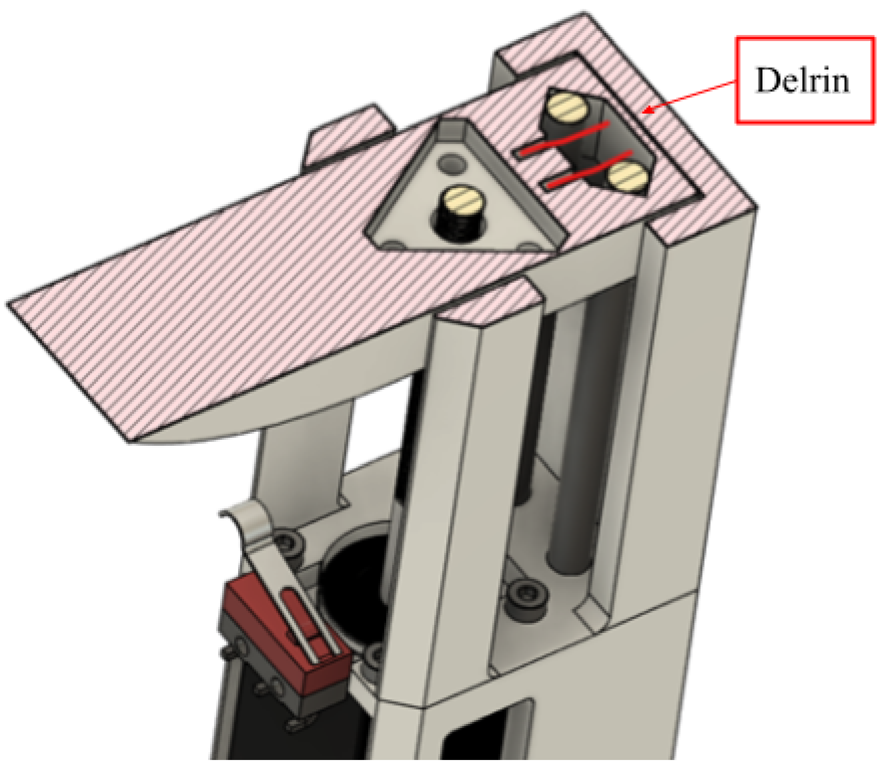



Figure 49: Cross section view of the cantilever, showing the Delrin chips (red), and how they contact the vertical rods.

## 3.1.2 Extruder Section

Attached to the end of the cantilever is a thermal separator and the hot end. The thermal separator is a small attachment between the cantilever and the hot end made of polyethylene terephthalate glycol (PETG), and it acts as a buffer so the PLA in the cantilever does not warp from the heat of the hot end. PETG was chosen due to its higher glass transition temperature of 85°C versus 60°C in PLA (O'Connell, 2024).

The hot end consists of an extruder found in many other commercially available printers, such as in various Crealty Ender printers. Because the extruder type is a Bowden extruder, the drive motor is located on the side of the main frame, rather than directly attached to the extruder. A feeder tube guides PLA from the Bowden extruder to the hot end. A small fan is also attached to the heat sink to provide extra heat dissipation. Wires come out from the heater block and fans into the controller.

## 3.1.3 Eccentric Cam Base Connection

The eccentric cam allows the Z-axis to lock itself into the frame, where users can easily fold it for portability purposes. A central shaft goes through the width of the frame and axis, which serves as a pivoting rod. At one end of the shaft is an hourglass locking mechanism, shown in Figure 50 below. The shaft can be inserted into the frame when the hourglasses are aligned, but when rotated 90 degrees, the shaft is unable to be extracted.

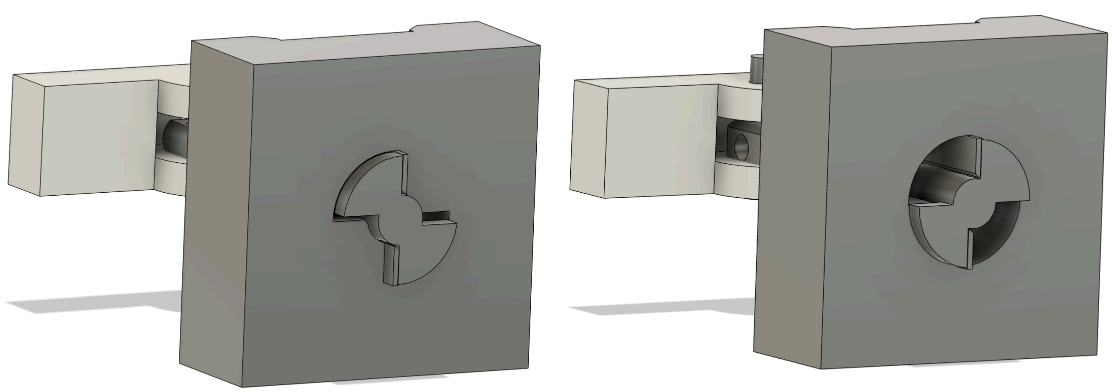


Figure 50: The Hourglass Locking Mechanism. On the left is the unlocked position, while on the right is the locked position.

On the opposite side of the shaft is the eccentric cam. The difference in length between its short and long radii is 1.6 mm. In its unlocked state, the cam is not pressed against the Z-axis, allowing it to fold over. When the cam is in a locked state, the longer distance in radius forces the cam against the Z-axis frame, restricting it between the hourglass locking mechanism flange and the cam. To ensure a tight fit, rubber was used on the relevant contact points between the hourglass flange and its contact with the base, allowing for slightly higher compression between the Z-axis frame and the base while simultaneously increasing the friction between the hourglass flange and the base. This created a better fit to ensure that the Z-axis frame would remain locked in position in its "engaged" state.

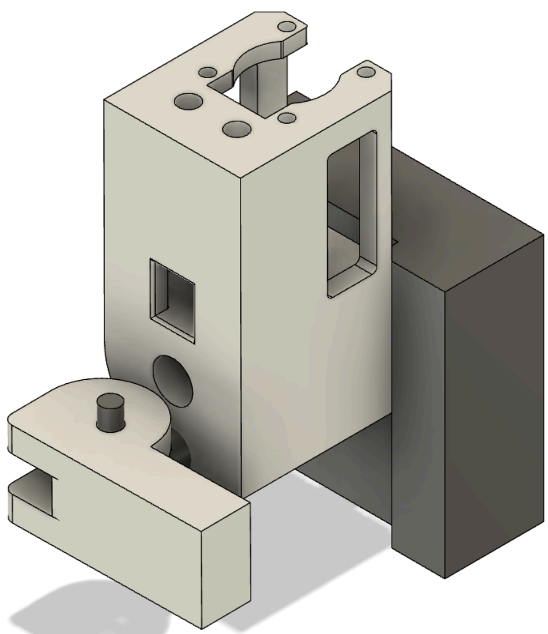


Figure 51: Eccentric Cam Connecting the Z-Axis Frame to the Main Frame.

The Z-axis frame is shaped as a vertical feature to fit into the main frame. Its corners are chamfered to press into its corresponding negative on the main frame. As the feature is the whole size and length of the Z-axis frame, the contact between the two frames is maximized. These two profiles prevent rotation along the locking pin and eccentric cam mechanism's main axis during the cam's engagement. This ensures the Z-axis frame is locked sturdily against the main frame. This mechanism can be seen in Figures 51 and 52.

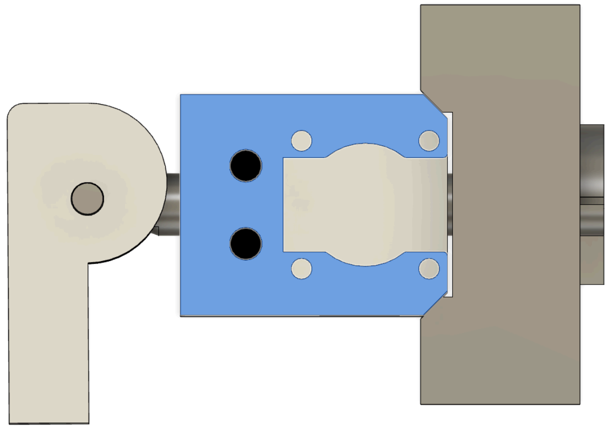


Figure 52: Top-Down View of the Locking Mechanism. Note the blue Z-axis frame's shape locks into the dark grey main frame. The slight gap between the Z-axis frame and main body ensures that the primary contact surfaces are the chamfered edges rather than their flat faces, allowing the full force of the cam mechanism to be applied to these edges and therefore allowing them to guide the Z-axis frame into its proper engagement position.

### 3.1.4 Hot End and Thermal Block

As mentioned in Section 1.2.1, 3D printers use a component called the hot end to melt and extrude filament, as seen in Figure 53 below. PLA is typically printed between 180°C - 220°C, and when the hot end is heated to full temperature, heat moves from the hot end through the heat sink. While the heat sink nearly cuts the temperature from the hot end in half, it does not prevent residual heat from causing our PLA parts to melt or creep. To validate that our materials withstand the heat from the heatsink, we located an Ender 3 printer with an identical hot end. The Ender 3 was preheated to 210°C and an infrared thermometer was used to record the temperature of the top of the heat sink. The temperature was found to be 120°C - a 54% reduction in temperature.

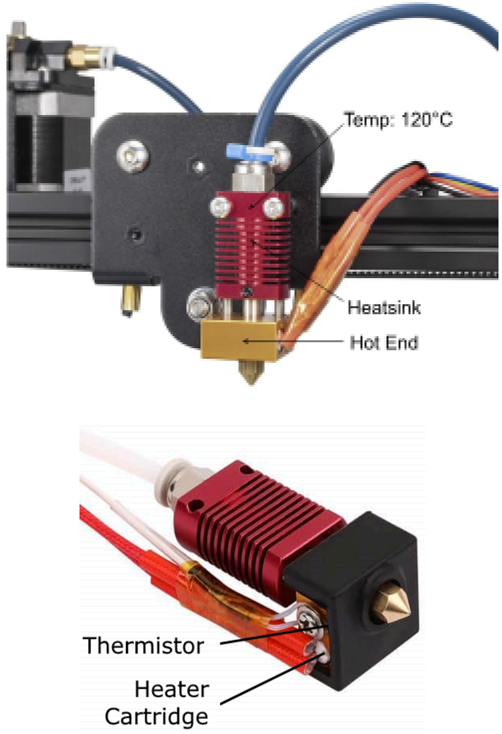
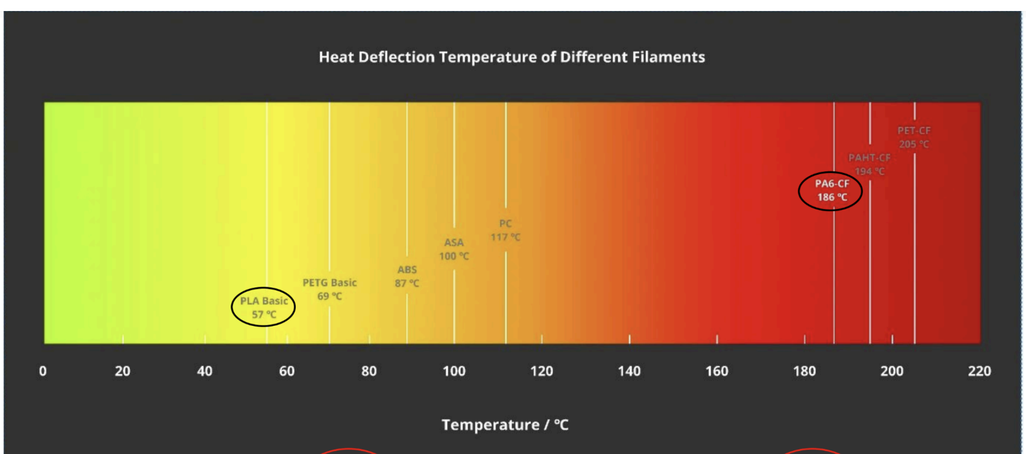



Figure 53: Ender 3D Printer Hot End (Creality Experts, n.d.)

With a transition temperature of approximately 60°C (Bambu Lab, 2023), our data suggests that PLA is insufficient and should be replaced with a material capable of withstanding temperatures ≥ 120°C.




| Filament | PLA Basic | PETG Basic | ABS | ASA | PC | CF - Nylon | PAHT-CF | PET-CF |
|---|---|---|---|---|---|---|---|---|
| Heat Deflection Temperature / °C (0.45 MPa) | 57 °C | 69 °C | 87 °C | 100 °C | 117 °C | 186 °C | 194 °C | 205 °C |

Figure 54: Heat Deflection Temperatures for Common 3D Printing Filaments (Bambu Lab, 2023)

According to Figure 54 above, CF - Nylon, PAHT - CF, and PET - CF are the only materials capable of withstanding ≥ 120°C. A block was designed and printed out of carbon fiber infused nylon filament - tripling the thermal resistance of the Z-axis. The location of this block is depicted below in Figure 55. This material resists warping at full temperature and worked perfectly for the intended application. Details regarding the results of simulative thermal analysis of the extruder and Z-axis materials through Ansys can be found in Section 4.1.

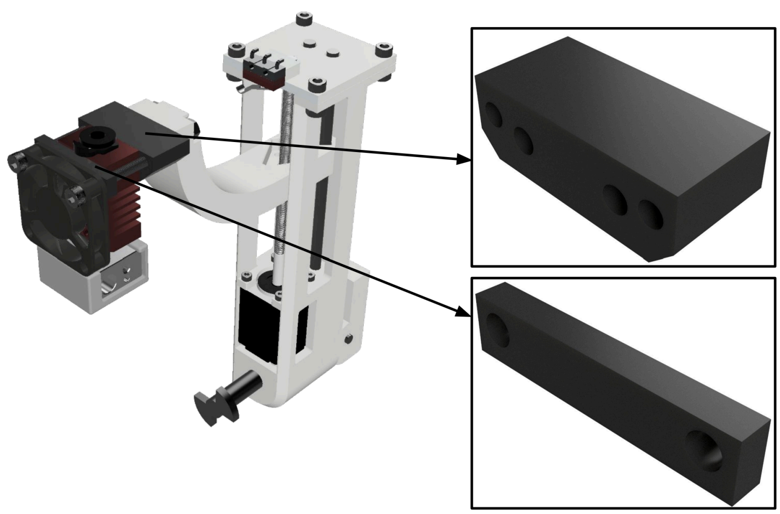


Figure 55: CF - Nylon Thermal Resistance Blocks

### 3.1.5 Assembly

With the components mentioned above, the Z-axis requires that a specific order be used for proper assembly. It is important to note that no glue is required to assemble the Z-axis at any stage. First, it requires that the anti backlash nut be secured to the cantilever arm via three M2 screws with nuts. This clamps the anti backlash nut to the cantilever, and coupled with the recess it fits into, locks the two components together. An anti backlash nut is used to ensure that the motion remains constant with minimal room for error when the drive motor is engaged. This motion would be greatly detrimental to the print quality of any parts used on Palm Print should it be allowed. The Delrin chips can then be inserted into the cantilever arm by pushing them into place.

Then, the hot end is installed to the cantilever arm. To do so, the large nylon spacer block must be attached to the cantilever, while the heat sink itself will be attached using the same screws. Insert two M3 socket head cap screws with nuts into the heat sink's holes and then the innermost through holes on the spacer and begin to thread the screws into the nuts. The nuts should be inserted into the corresponding recesses on the cantilever arm and both tightened until they are secured. At this point, the hot end should be secured to the cantilever arm, sandwiching the large spacer block in between. This can be seen in Figure 56 below.

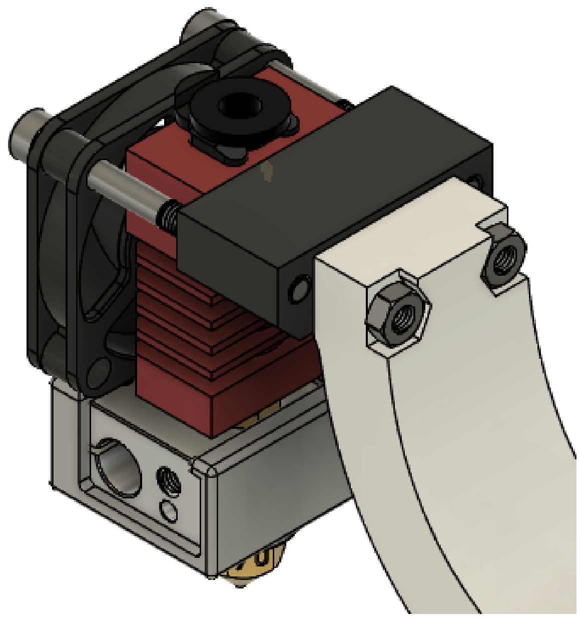


Figure 56: The Extruder Hot End and its Mounting to the Cantilever Arm

The fan subassembly attaches to the front of the heat sink via two shanked M3 socket cap screws. These start by going through two holes on the fan, then through the small spacer block, and threading directly into the outermost holes on the large spacer block. These are tightened only until the fan is secured, keeping in mind that over torquing these screws will strip the threads out of the large spacer block, rendering it nonfunctional. Note the heads of the screws securing the hot end itself come in contact with the small spacer, providing an additional air gap between the fan and the heat sink.

The NEMA motor with the lead screw is installed into the frame with four M2 screws first. Next, the guide rods are inserted into the frame, being pressed into their designated holes and through the cantilever arm. It is fine to use moderate force to insert these, as it is intended to be a press fit. These rods are also constrained at the lid of the Z-axis. At this time, the lead screw should be turned so that the cantilever arm is lowered. This can be done either by hand or by turning on the motor. The lid of the Z-axis goes on top of the mechanism and is screwed into the frame with four M3 screws and their corresponding nuts. The lid partially constrains the lead screw, preventing it from wobbling, whilst allowing it to rotate. The limit switch is attached to the lid, facing downwards. This is how the cantilever homes, as it moves upwards until it hits the limit switch. Section views of the Z-axis can be seen in Figure 57.

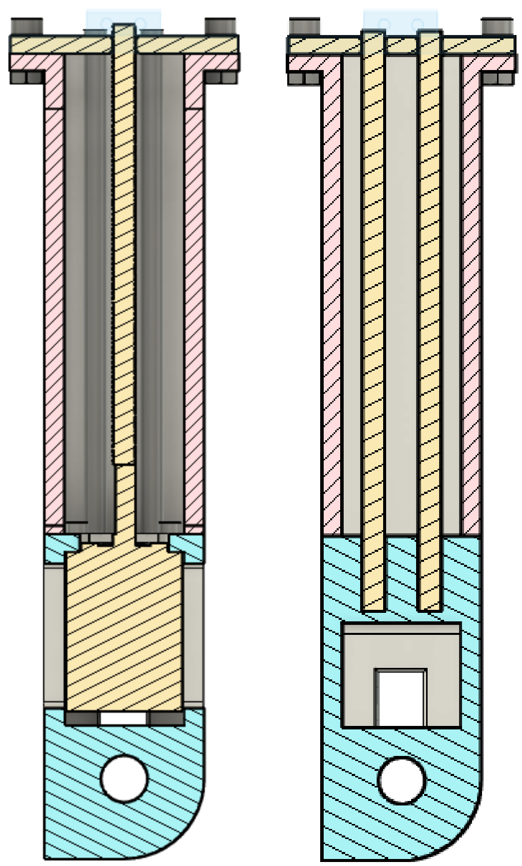


Figure 57: (Left) Section View of the Motor and the Lead Screw. (Right) Section View of the Guide Rods and their Press Fit into the Frame.

Attaching the Z-axis to the main body frame requires attaching the eccentric cam to the Z-axis. The hourglass shaft is first placed through the main rotating hole at the bottom of the Z-axis. Aligning the hole of the eccentric cam with the hole of the hourglass shaft, a 4mm metal pin is placed through the eccentric cam and hourglass shaft, acting as a pivot between them. The hourglass shaft is then inserted into the hourglass hole on the main frame, then rotated to lock the

Z-axis from moving outwards. The eccentric cam can then be pulled back gently, to lock the Z-axis into the main frame.

## 3.2: Linear Guide Rail Printer

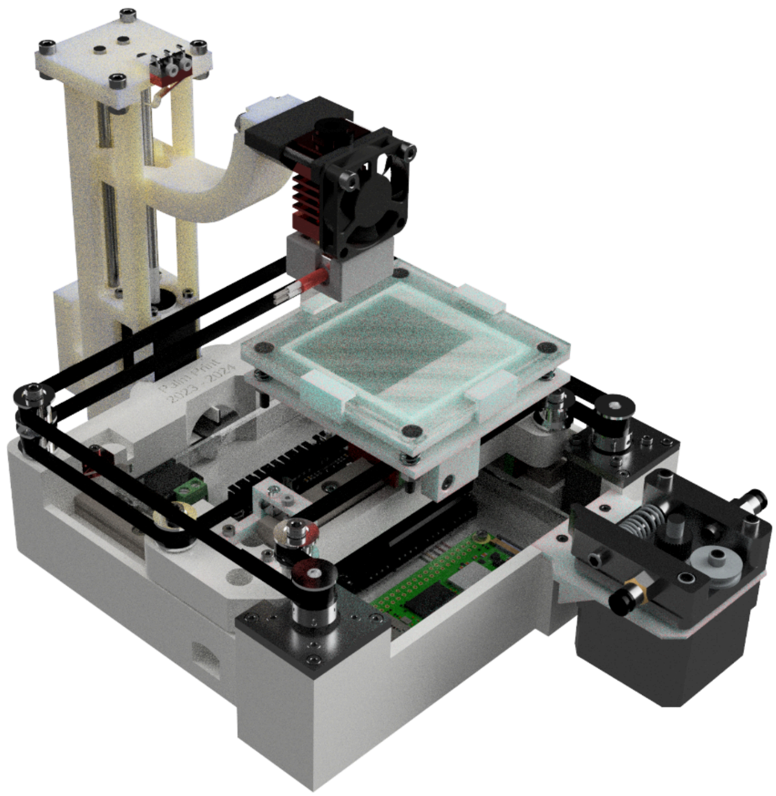


Figure 58: Fusion 360 Linear Guide Rail Assembly Render - Isometric

The linear rail design, shown in Figures 58 through 61, uses the CoreXY coordinate configuration for its bed and extruder movement. Motion in the X and Y directions was achieved using two motors, belts, pulleys and linear guide rails. The motors, belts and pulleys are set up as described in the CoreXY printer configuration section. The linear guide rails are what make this printer different from the other designs. Linear guide rails use rolling balls within the carriage on the guide rail to reduce friction and allow the carriage to move effortlessly along the rail (Figure 11). Using three guide rails, one on either side of the gantry and one on top for our print bed, we are able to get our X and Y movement.

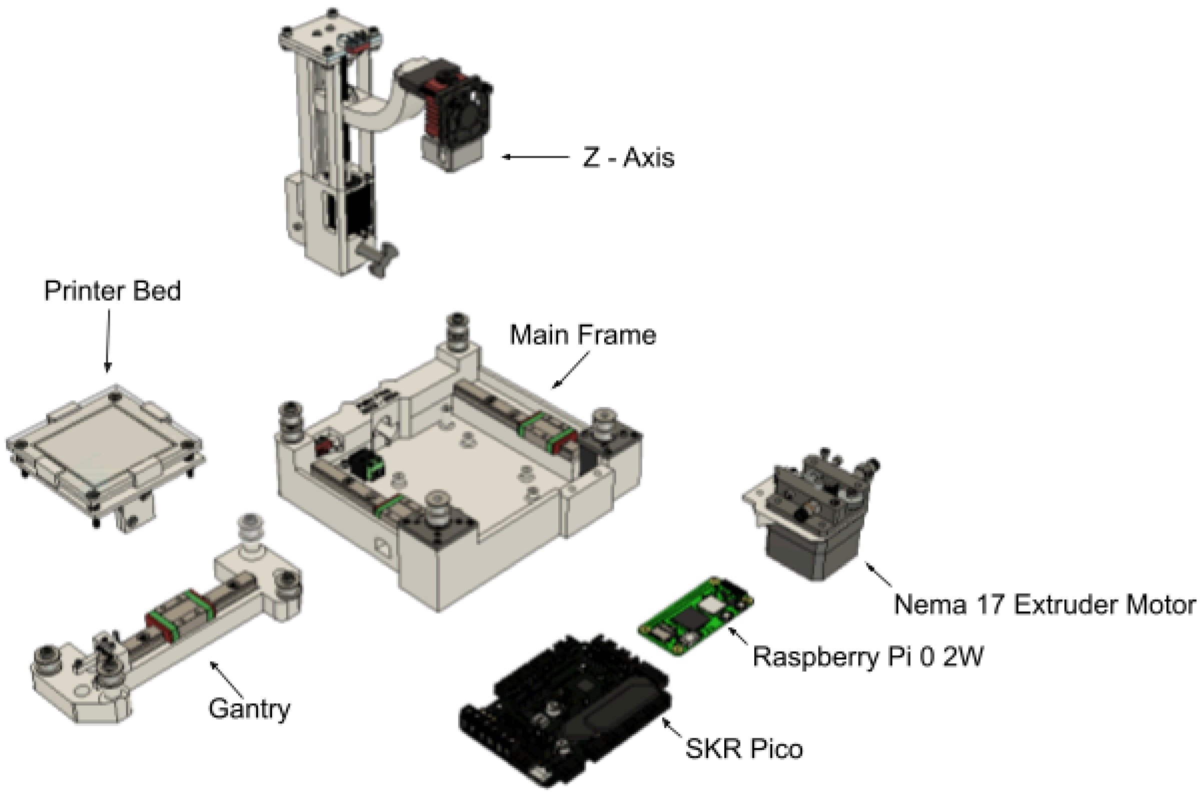



Figure 59: Exploded View of Linear Rail Components

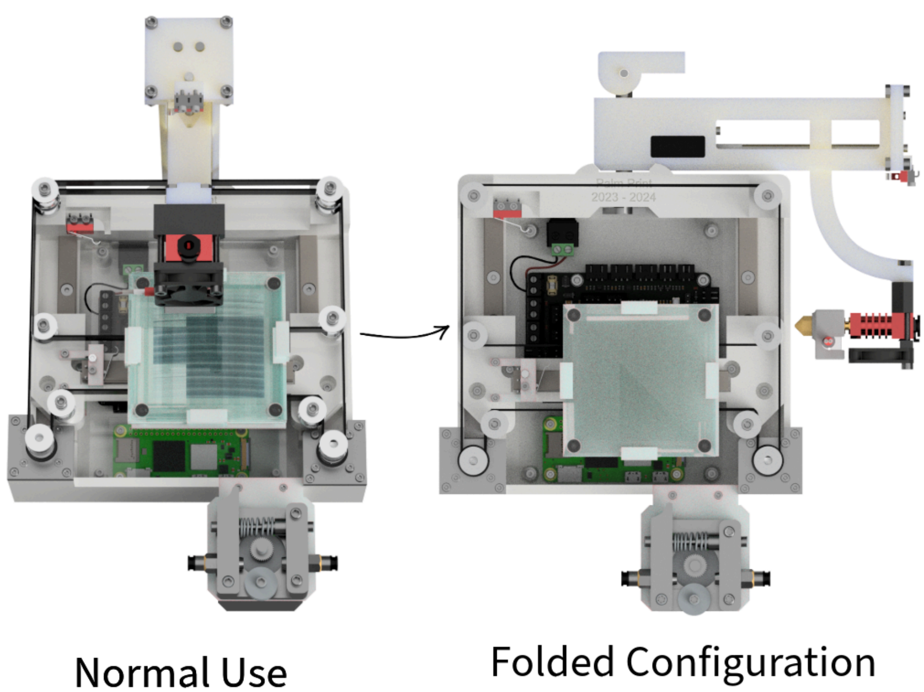



Figure 60: Normal Use (bottom left) vs Folded Z-Axis Configuration (bottom right)

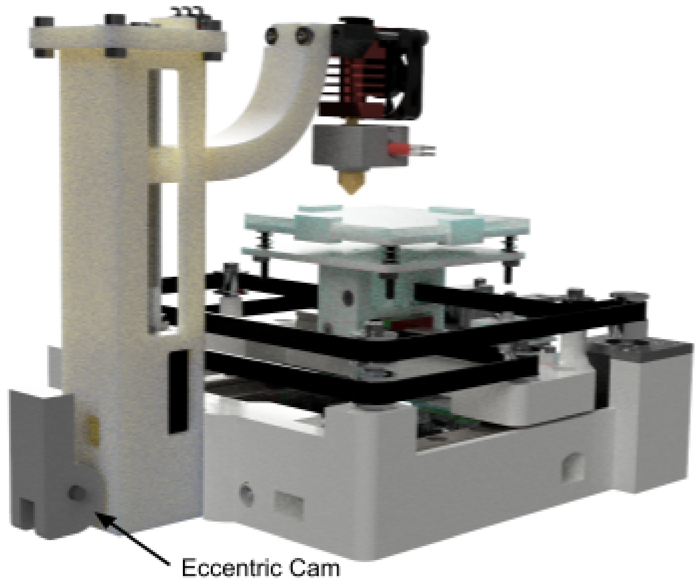



Figure 61: Linear Rail Model with the Eccentric Cam Identified

### 3.2.1: Linear Rail Gantry

The gantry is the middle section of a 3D printer that allows the print bed to move in the X and Y direction. This gantry features a single linear rail that supports smooth movement in the X direction which improves print quality; unintended movement in the gantry affects the leveling of the bed which can impact the print quality if the bed is not perfectly leveled.

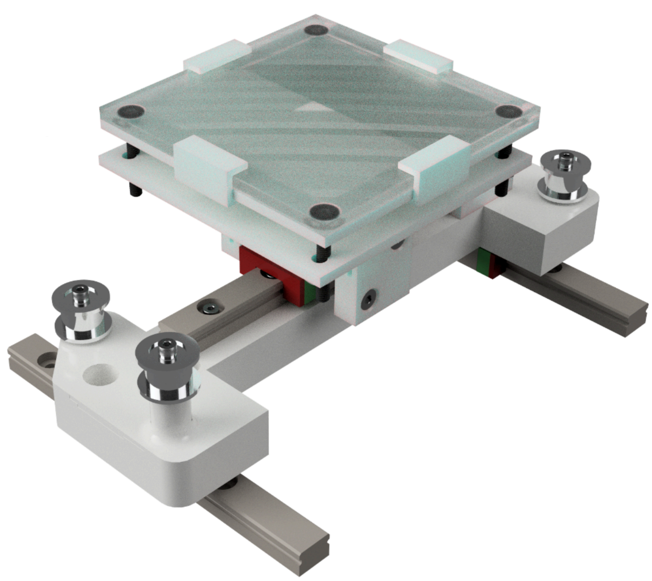


Figure 62: Isometric Render of the Linear Rail Gantry

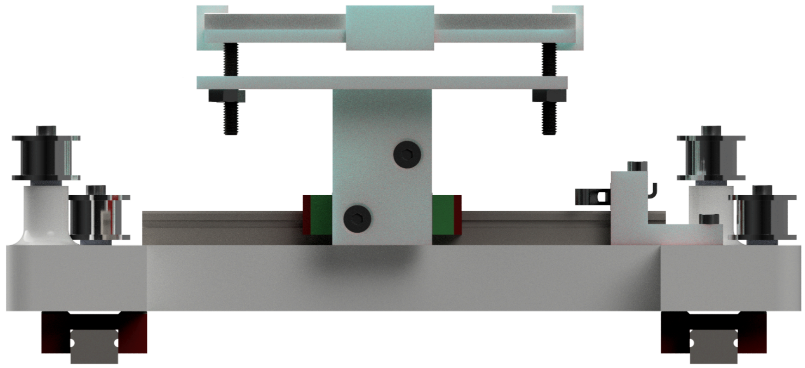


Figure 63: Front Render of Linear Rail Gantry

CoreXY printers often use double-stacked pulleys to move the print bed and hot end simultaneously. Spacers were incorporated into the design to allow for the belts to be double stacked. The linear rail gantry can be seen in Figures 62 and 63 above.

### 3.2.2 Linear Guide Rail Bed Holder

The print bed is attached to the linear guide rail carriage on top of the gantry. Because it has 4 mount points on the carriage, it completely eliminates any rocking motion and keeps the bed level. This is important as any difference in the bed level or tilting during printing can cause print failure. The bed holder is attached using four M2 screws, one at each of the mounting points on the bottom. For easier bed leveling, the glass bed is attached to the holder using springs. This was accomplished by a square piece of PETG attached to the bed holder using 4 flat head screws in each corner. On each screw, between the plate and bed holder is a spring, to allow the plate to be tensioned level with a simple allen key. With a level square plate, the glass bed is attached using a clip on each side. These clips are outside the build coordinates so the extruder will not interfere with them while printing. The linear rail print bed can be seen below in Figure 64.

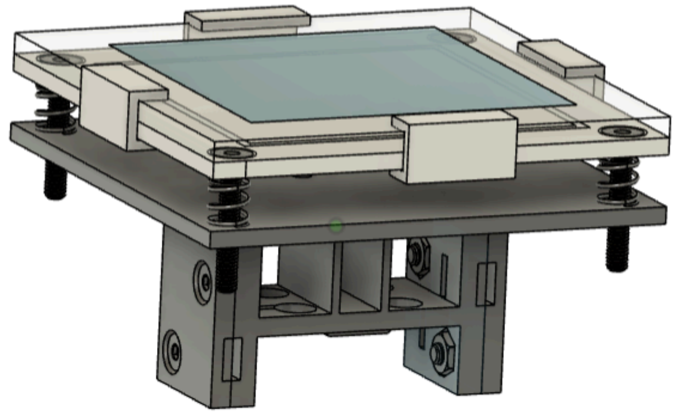


Figure 64: Linear Rail Print Bed Assembly

The belts are attached to either side of the bed holder using the custom belt tensioner. There are two slots on either side, the top two for the upper belt, and the bottom two are for the lower belt. The belt will go through the slot from the inside, and then fold back towards itself once on the other side. There are grooves cut into the side of the bed holder to hold the belt more securely. The tensioner plate will then go over the outside, pressing the belt into the grooves. The plate is secured to the bed holder using two screws and nuts. The belt is then pulled to achieve the required tension. The exploded view can be seen in Figure 65 below.

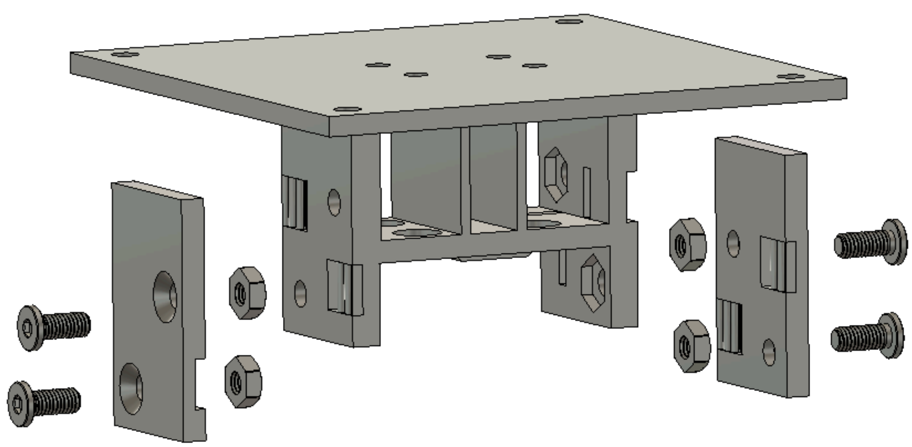


Figure 65: Belt Tensioners Exploded View

### 3.2.3 Limit Switches

Palm Print uses three limit switches to define the maximum or minimum position that each of the axes can travel. The limits for palm print are:

X Direction: 0mm - 50mm (Limit Switch located at 0mm).

Y Direction: 0mm - 50mm (Limit Switch located at +50mm).

Z Direction: 0mm - 40mm (Limit Switch located at +40mm).

At the start of each print, Palm Print performs a homing sequence to find the origin of the print bed (0, 0, 0). Each axis individually moves back and forth until the limit switch is pressed and the origin is located. By incorporating limit switches, the printer can accurately determine the bounds of its build area, ensuring that the print head and build platform operate within safe limits. This helps to prevent collisions and potential damage, but also allows the printer to accurately position the print head and build platform during the printing process for precise and consistent print quality. Locations of each limit switch can be seen below in Figure 66.

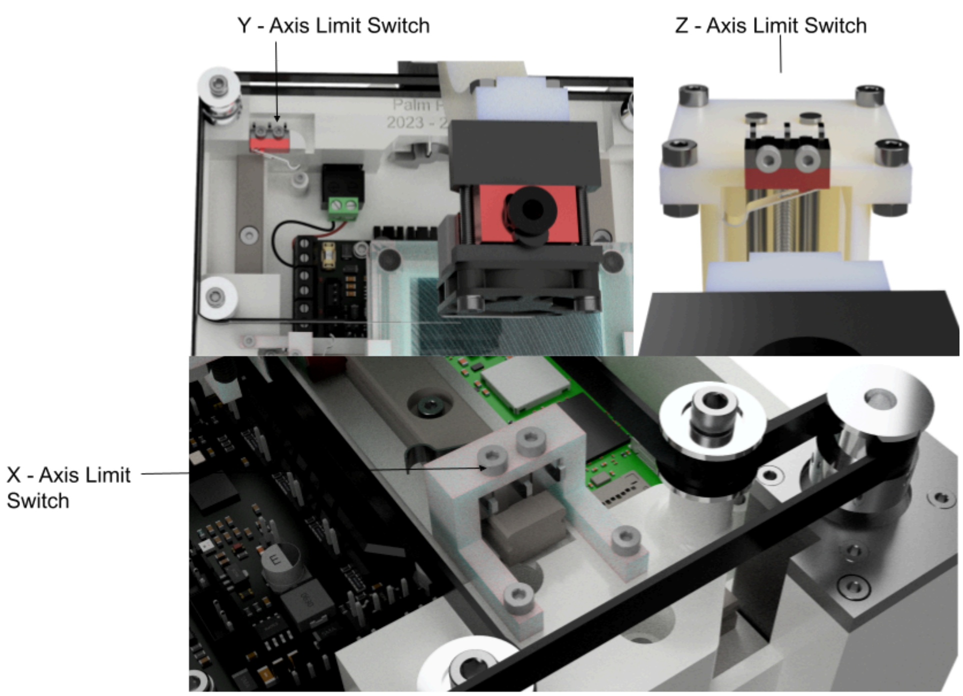



Figure 66: Limit Switch Locations

### 3.2.4 Specifications

**Table 2: Linear Rail Printer Specifications**

| Items | Specifications |
|---|---|
| Build Volume | 50 x 50 x 40 $mm^3$ |
| Printer Size (Printing Configuration) | 150 mm (L) x 135 mm (W) x 165 mm (H) |
| Method | Fused Deposition Modeling |
| Printer Weight | 1324 g |
| Filament Diameter | 1.75mm |
| Nozzle Diameter | 0.4mm |
| Filament Type | PLA |
| Bed Type | Borosilicate Glass |
| Power Supply | DC12 V, 30.0 A |
| Firmware Type | Klipper |
| Connectivity | USB, Local Website (palmprint.local) |
| File Type | G-Code |

## 3.3: Linear Rod Printer

The linear rod design uses linear rods as the linear guide method for the bed movement in the X and Y directions. Like the linear rail design in Section 3.2, the CoreXY coordinate system is used to move the bed in the X and Y directions while the Z-axis moves independently in the vertical direction. The X and Y motion was powered the same way as described in the linear rail design, with motors, belts, and pulleys; however, the linear rod system is used as a guiding system in place of the linear rails. To achieve the linear movement in the Y direction, a set of linear rods were used as a track, and a second set of linear rods was used to hold the gantry in place. Movement in the X direction was guided by a singular guide rod and a vertical slot containing Delrin material. The components of the design can be seen in Figure 67.

Due to financial and time constraints, this design was only modeled mechanically and was not tested electronically. However, the base was designed to be able to contain all the electronics used in the linear rail design and therefore has the capability to be tested in the future.

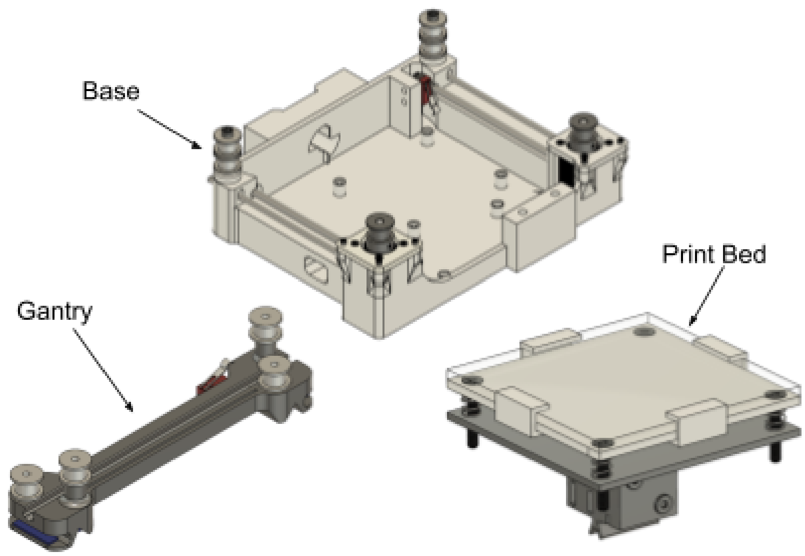



Figure 67: Main Components of Linear Rod Design including the Base, Gantry, and Print Bed

## 3.3.1: Linear Rod Base and Gantry

The base of the linear rod design consists of two motor housings for Nema 8s in the front and two pairs of double stacked toothless pulleys in the back. There are two pairs of linear rods that help guide the gantry's linear movement.

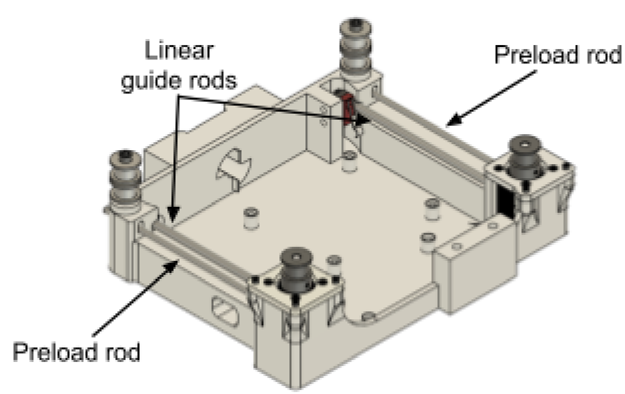



Figure 68: Linear Rod Base with the Linear Rod Functions Specified

Although traditional designs use bearings with linear rods, the team decided to have the gantry directly sliding on the rods to better control the degrees of freedom, depicted in Figure 69. As seen in Figure 68, the inner linear rods guide the gantry in the Y direction, while the outer ones hold the gantry in place. The gantry has a V-shaped cutout on each side that sits perfectly on the inner rods. Delrin material was placed In the areas where the gantry contacts the rods, to reduce the friction between the PLA gantry and the steel rods. A cross section of this can be seen in Figure 70.

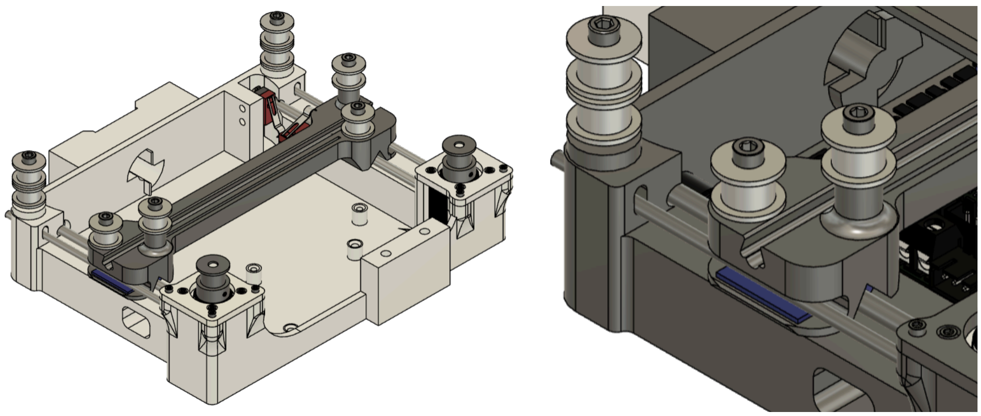


Figure 69: The Gantry Sliding on the Linear Rods (left) with a Close-up of the Mechanism (right)

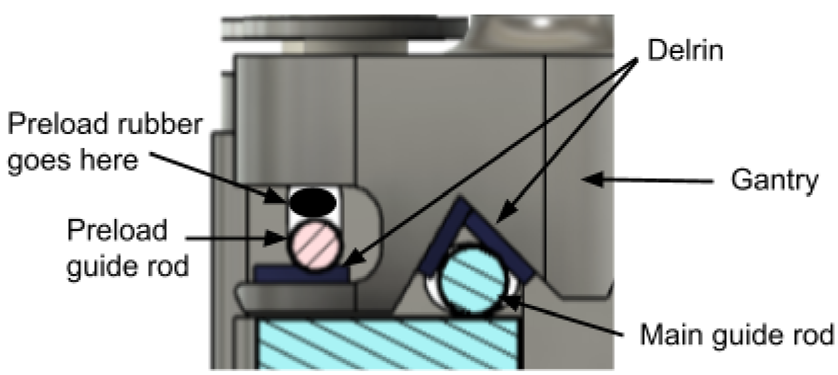



Figure 70: Cross Section of the Gantry with the Linear Rods.

Since the linear rods needed to be completely parallel, one of the guiding rods needed to be designed to have some give. Although the parts were drawn to be completely parallel, the printed prototype often has some discrepancies. To prevent the gantry from binding, the slot for one of the rods was shaped as an ellipse as shown in Figure 71. The other slot was designed to restrict all movement of the other rod. This was designed as a teardrop shape to provide the required constraint while also allowing the feature to print with better quality.

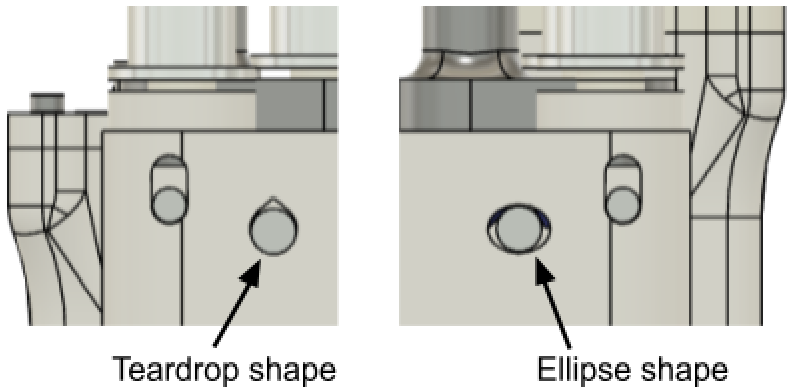



Figure 71: Cropped Back View of the Linear Rod Design. The slot that holds the rod on the right is shaped like an ellipse to allow for minimal movement which prevents binding (right) while the teardrop shape restricts movement and allows for accurate printability (left)

To keep the gantry secured whilst allowing movement, a rubber preload was added to the assembly. The smaller rods on the base fit over the tabs on the gantry as seen in Figure 70 with small rubber pieces pressing down on the rods. This helped eliminate a majority of rocking and twisting that would occur when there was no pressure on the gantry.

To control the movement of the gantry and bed holder, one limit switch for each direction was incorporated into the design. For the X direction, the limit switch is mounted onto the gantry. The switch is activated when the bed holder slides over top of the switch. The switch that controls the Y direction is mounted in the back right corner of the base and is activated when the gantry hits it. The placement of the limit switches for the linear rod design can be found in Figure 72.

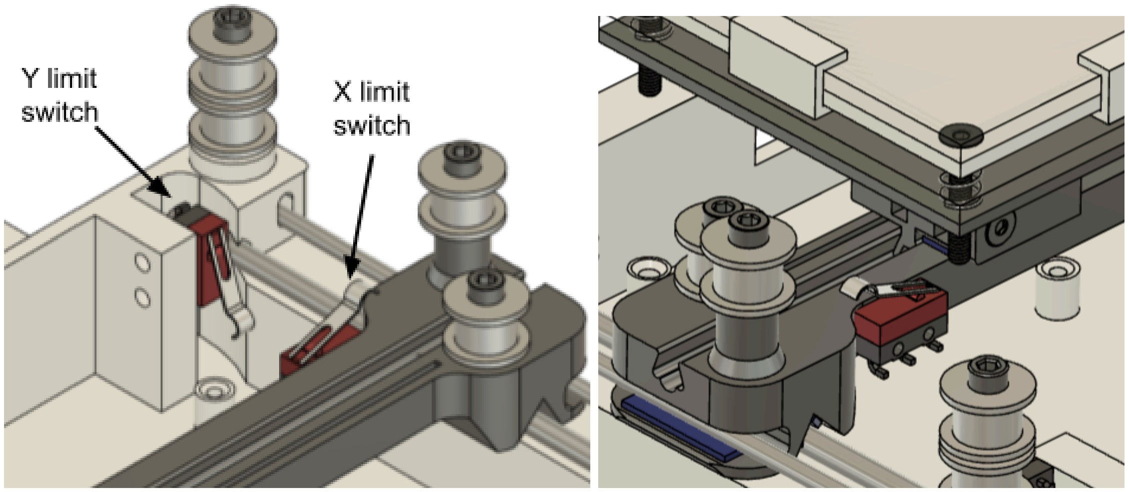



Figure 72: Limit Switch Locations for both X and Y Movement (left) and a Close up of the X Limit Switch (right)

As a part of the CoreXY system, the gantry holds four pulleys as seen in Figure 73 that line up with the pulleys on the base. To save space, the pulleys were double stacked. Because of this, special attention had to be paid to the gantry and bed holder height dimensions to ensure the pulleys would all line up properly. Details of this can be seen in Figure 100 in Section 3.4.2.

### 3.3.2: Linear Rod Bed Holder

The linear rod print bed slides along a 3mm x 100mm rod within the gantry. This is done by creating an upside-down V-cut throughout the middle of the gantry. The bottom edges are rounded, with the rod going between them. The bed holder has an upside-down V extruded on the bottom. The setup can be seen below in Figures 73 and 74.

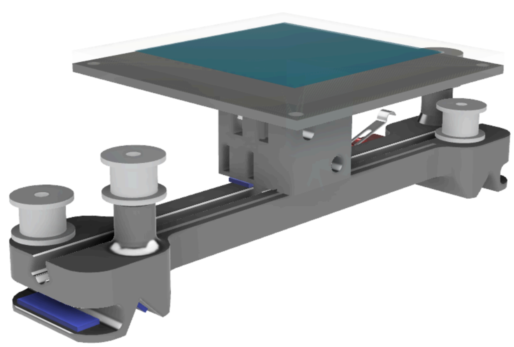


Figure 73: Rendering of Gantry and Bed Holder

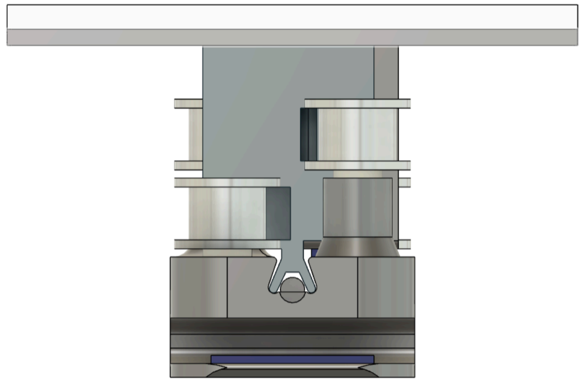


Figure 74: Side View of Linear Rod Print Bed

The upside-down V setup allows the bed holder to ride along the rod, while also preventing it from being pulled out of the top. If friction is a major concern, the bed holder would have been made from Delrin. After testing, the bed holder moved smooth enough across the gantry while being made of PLA and did not require the material change. The bed did; however, rock from side to side, as the rod acted as a single mounting point. To reduce this movement, a slot was put in both the bed holder and gantry, shown in figures 75 and 76.

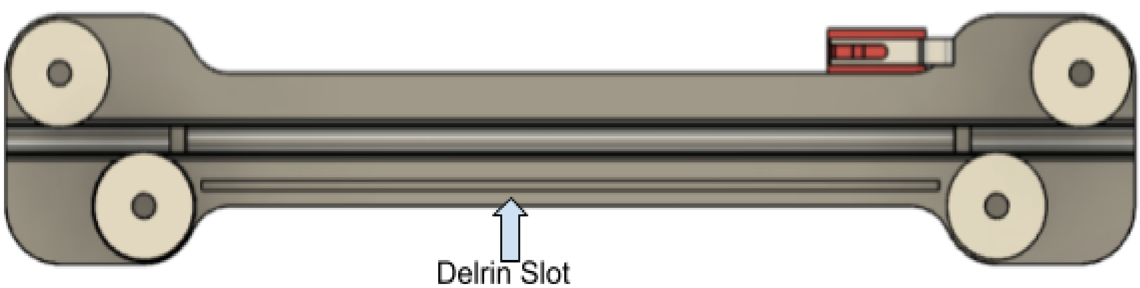



Figure 75: Top View of Linear Rod Gantry

A piece of Delrin was inserted into the slot on the bed holder. This Delrin will slide down the gantry with the bed holder, reducing the rocking motion from side to side.

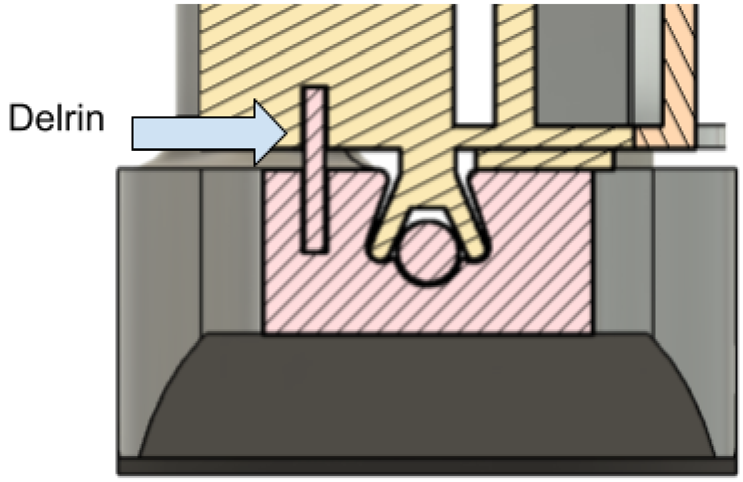



Figure 76: Section View of Bed Holder and Gantry Connection

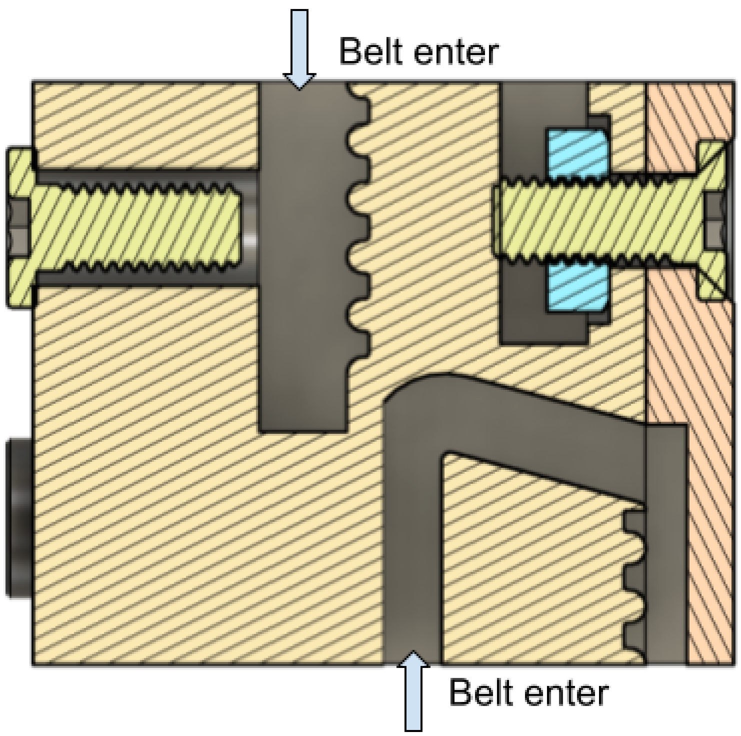



Figure 77: Section View of Linear Rod Print Bed From Top

As shown in Figure 77 above, the belt tensioner works the same way as described in Section 3.2.2. Due to the slots being further in the holder, the cuts pushing the belts out through the tensioner had to be angled. The belt tensioner is only on one side of the linear rod version, however. The other side consists of a slot for the belt, and a screw that will clamp the belt down. Within these slots are grooves for the belt to dig into and hold more securely. With the bed holder being made of PLA, we had to put threaded inserts (not shown in figures) into the holes to give the screws something to grip. This side is only for securing the belt to the bed holder, the other side with the tensioner allows for the tightening or loosening of belts.

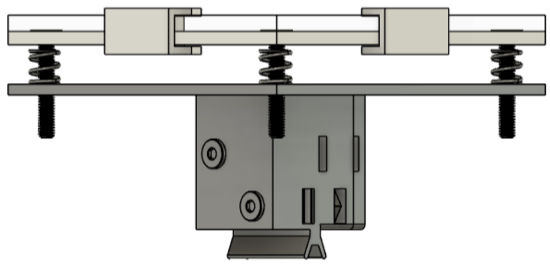


Figure 78: Angled View of Belt Mounts and Slots

The print bed itself is detachable and consistent amongst all three designs. The top plate of the holder is the same size as the linear guide rail bed holder. The design and attachment of the print bed to the top of the holder is described in Section 3.2.2. The fully assembled print bed is shown in figures 78 and 79.

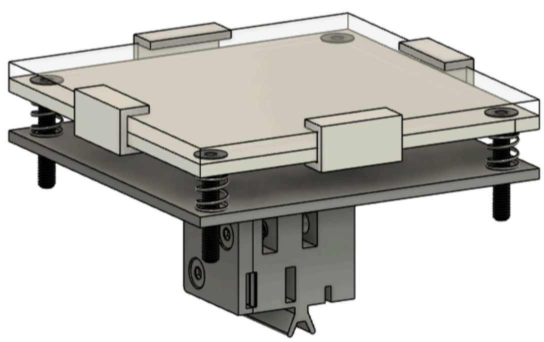


Figure 79: Linear Rod Print Bed Assembly

## 3.3.4: Linear Rod Full CAD Assembly

Figures 80 and 81 show the final CAD of the linear rod design. Belts are not included in the CAD as Fusion360 does not have an accurate way of modeling their assembly and movement.

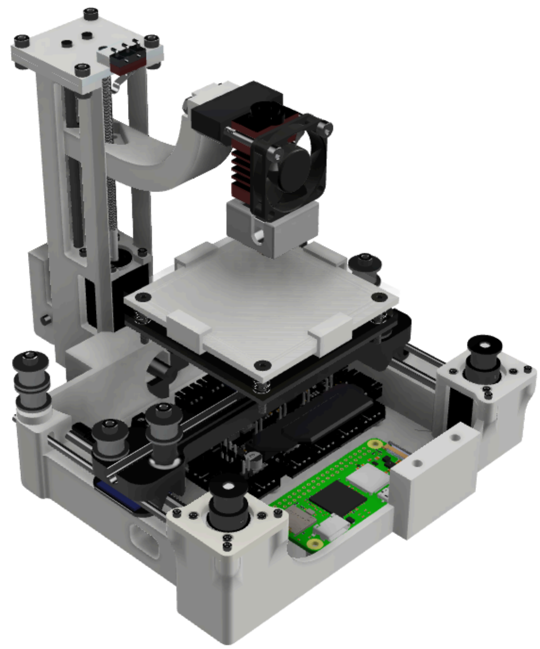


Figure 80: Full CAD Assembly of Linear Rod Design Isometric View

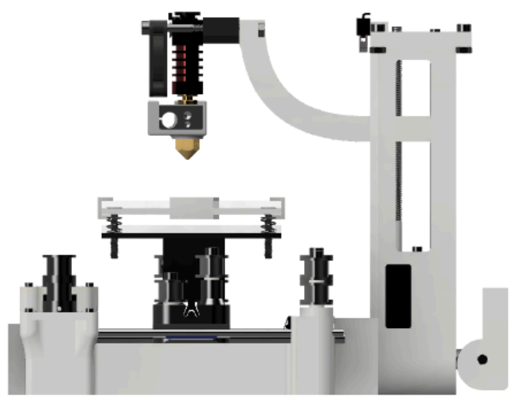


Figure 81: Full CAD Assembly of Linear Rod Design Right View

## 3.3.5: Linear Rod Final Prototype

The final prototype, shown in Figures 82 and 83, is only a mechanical model of the X and Y axis. This final design does not contain the Z-axis or electronics besides the X and Y motors. The team decided to have the Z-axis and electronics on the linear guide rail prototype.

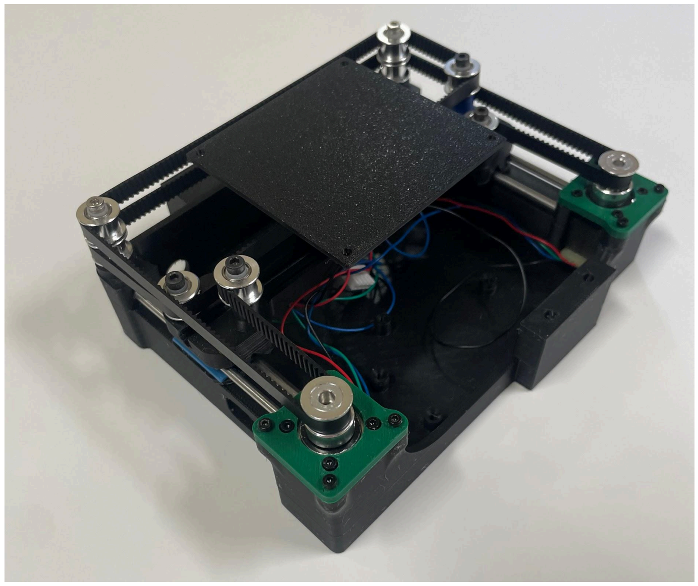


Figure 82: Final Prototype for X-Y Axis of Linear Rod Design Isometric View

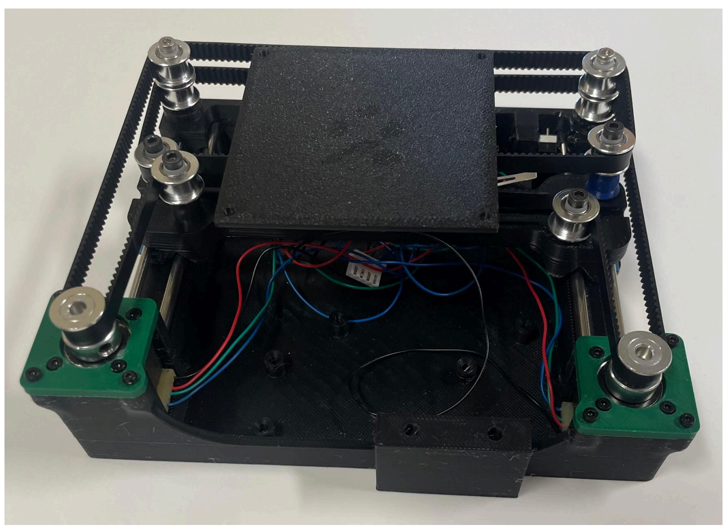


Figure 83: Final Prototype for X-Y Axis of Linear Rod Design Front View

## 3.4: V-Groove Printer

While the V-groove version of the Palm Print uses the same gantry movement as the linear rod design, the main component that makes it unique is the movement of the bed holder. This design features V-groove bearings in a triangular configuration traveling along parallel linear rods to produce the movement of the bed holder. Outside of the V-groove bearings, the second component that makes this version distinctive is the V-groove gantry, which is the PLA housing of the linear rods, gantry pulleys, and the limit switch. The original version of the gantry in its empty configuration can be seen below in Figure 84.

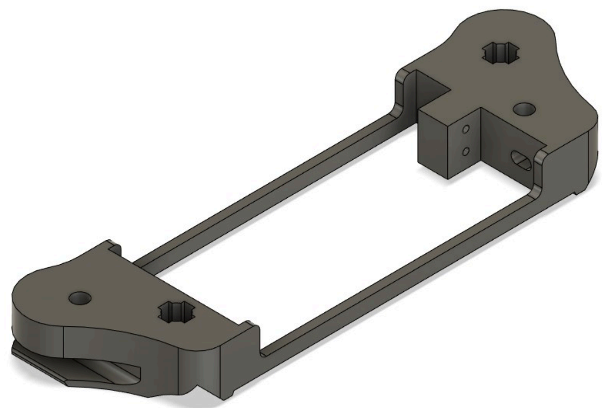


Figure 84: Original Version of the V-groove Gantry

The original version was altered due to it not providing enough volume for printing in the Y direction (front to back). The original V-groove had an overall width of 44 mm. The final version of the V-groove shrank to a width of 37 mm, providing 16% more printing capabilities in the Y direction. The final version of the gantry in its empty configuration can be seen in the Figure 85 below.

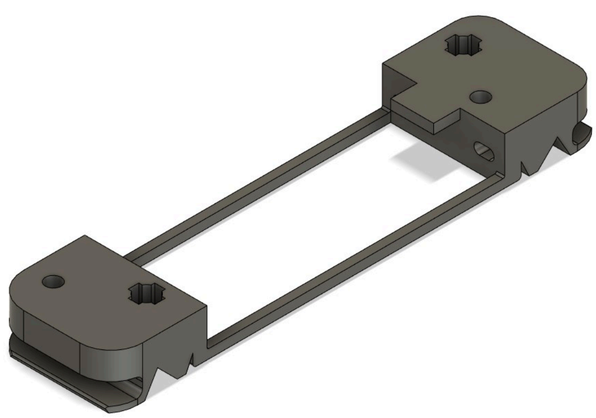


Figure 85: Empty, Final Version of the V-Groove Gantry

### 3.4.1: V Groove Bed Holder Movement

As mentioned in the Section 3.4 introduction, the bed holder is moved using three V-groove bearings attached to the bottom section of the bed holder in a triangular configuration. The triangular configuration and bottom bearing connection section is seen in Figure 86 and 87 below.

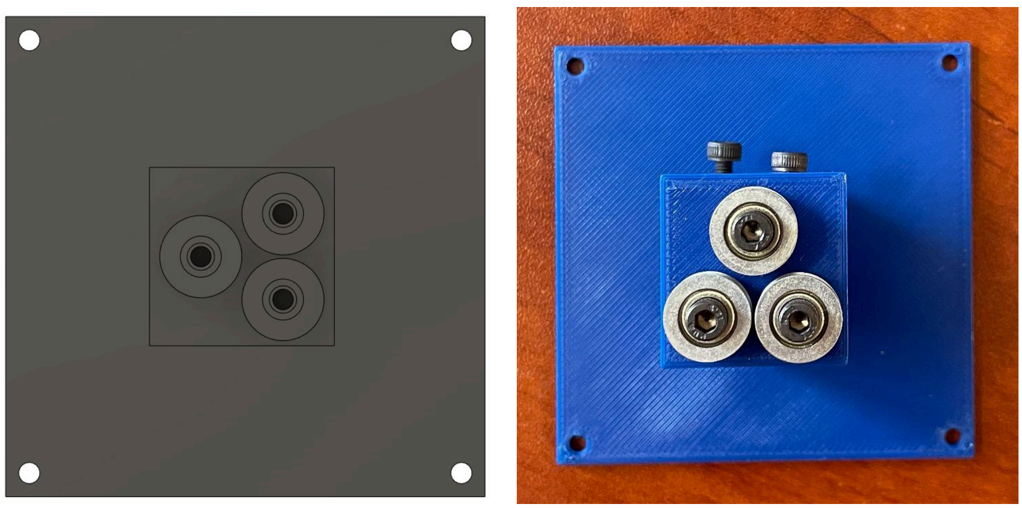


Figure 86: Triangular Bearing Configuration (Left: CAD, Right: Physical)


Figure 87: Bottom Rectangular Section for V-Groove Bearing Housing (Left: CAD, Right: Physical)

These V-groove bearings travel along the two parallel rods. This guides the bed holder linearly along the gantry, achieving the X-axis motion. These rods are inserted to the V-groove gantry through side holes. The interfacing between the gantry, rods, and bearings are depicted in the Figures 88 through 90 below.

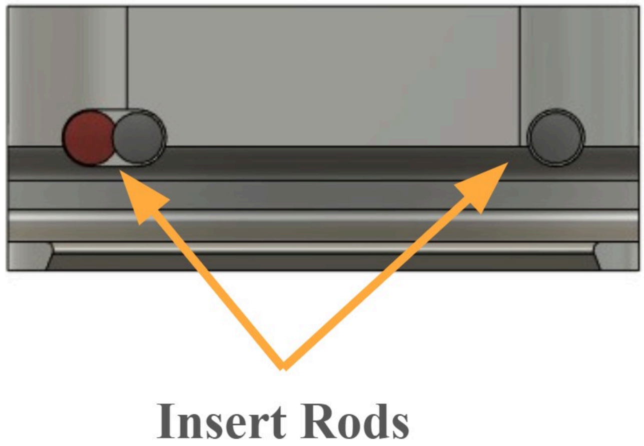



Figure 88: V-Groove Gantry Side Holes for Rod Insertion (Right View)

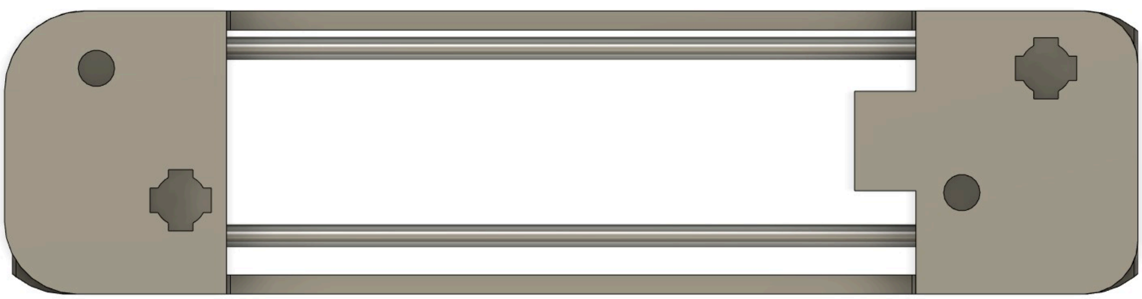


Figure 89: Linear Rods after Full Insertion (Top View)

Figure 90: Single Rod-Single V-Groove Bearing Travel Interface

Due to the triangular configuration of the bearing, one rod experiences more force than the other. For the bearings to travel along the rods, one had to be pre-loaded to mitigate binding of the bearings. If the rods are inserted without being perfectly parallel, it could cause binding, slipping, or other bearing issues. This is detailed in Figure 91 below.

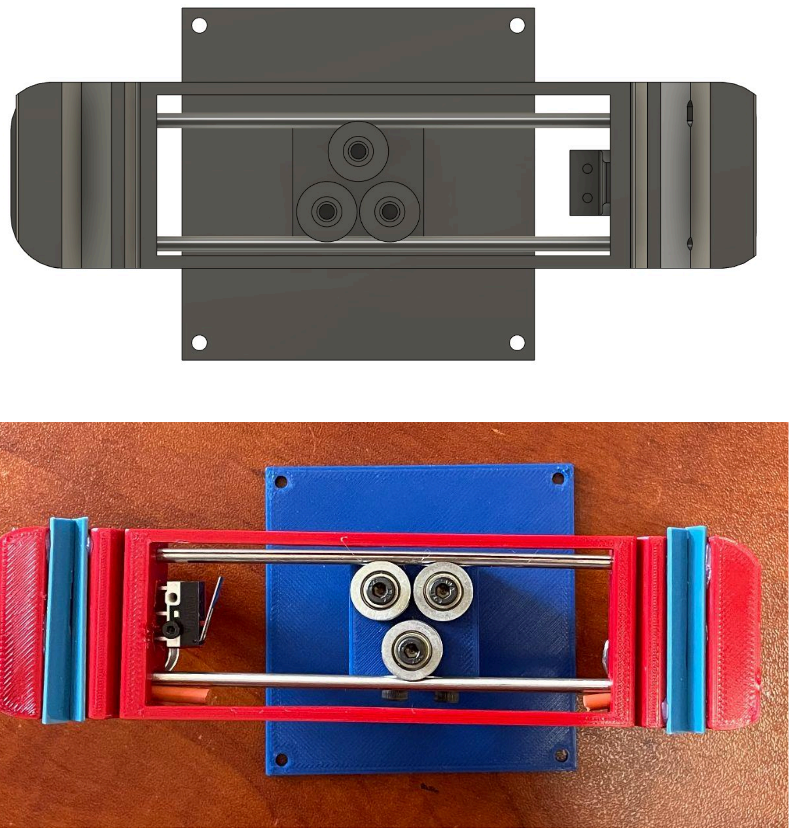


Figure 91: Triangular V-Groove Bearing Configuration-Parallel Rods Interface (Top: CAD, Bottom: Physical)

To balance the uneven distribution of the triangular configuration on the rods, one of the holes used for rod insertion was transformed into a slot to house a stiff, circular piece of rubber that acts as a preload. The rubber preload slot can be observed in Figure 92 below.

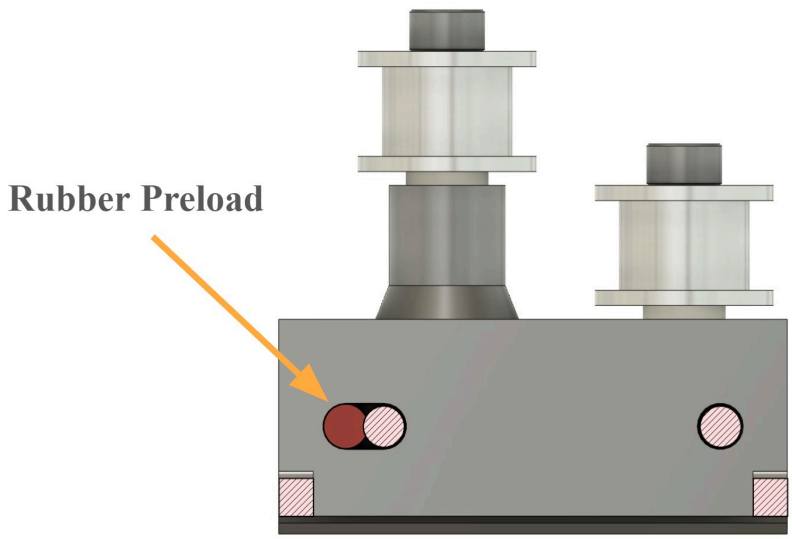



Figure 92: Parallel Rods with the Rubber Preload Housing Slot

The rubber applies a compressive force to the rod with one V-groove bearing to counteract the larger force applied by two V-groove bearings to the other rod.

When the bed holder and bearings are traveling along the rods, it can travel a maximum of about 80 mm due to the limit switch installed. This switch is connected to a designated rectangular section of the gantry that lines up with the holes of the switch. Figure 93 below shows the limit switch's position in the gantry.

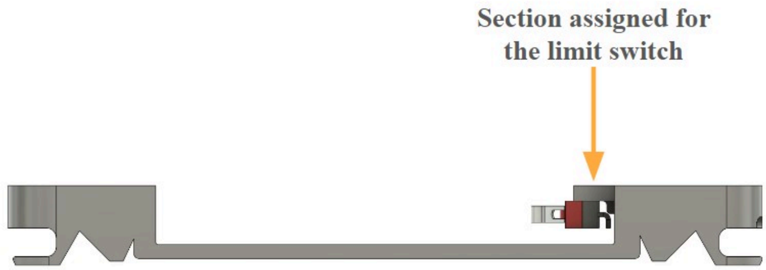



Figure 93: Limit Switch Position in V-Groove Gantry

The bed holder can travel this distance due to the belts, belt slots, belt tensioner, and pulleys. The V-groove bed holder has the same belt tensioner and slot design as the other two versions of Palm Print. The functions of these parts for the bed holder are detailed in Section 3.2.2.

The gantry pulleys, base pulleys, and motor heights must all be aligned with the slots of the bed holder. The bed holder slots were aligned with the pulleys which can be seen in Figure 94 below. Pulley alignment with the base for gantry movement is discussed in the next section, Section 3.4.2.

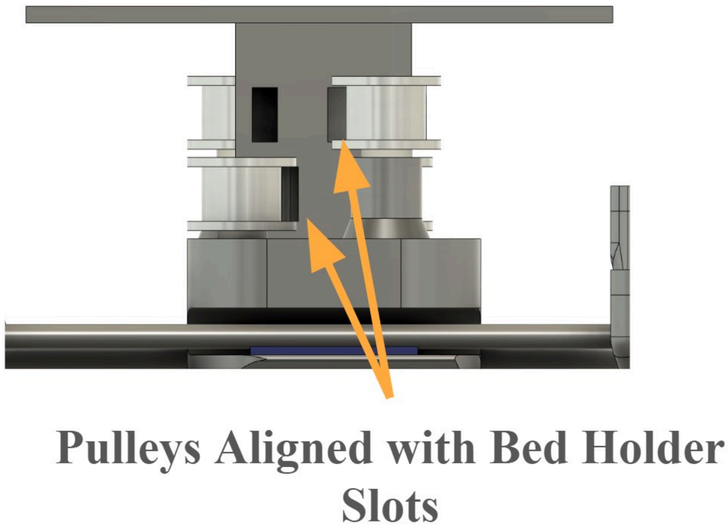



Figure 94: Gantry Pulleys Alignment with the Bed Holder Slots

The gantry pulleys are connected through different holes in the gantry that assign a specific height. The holes that are circular align with the shorter motor, base pulley, and bed holder slot heights. The holes that have rectangular slots match the taller motor, base pulley, and bed holder slot heights. The hole assignments are visible in Figure 95 below.

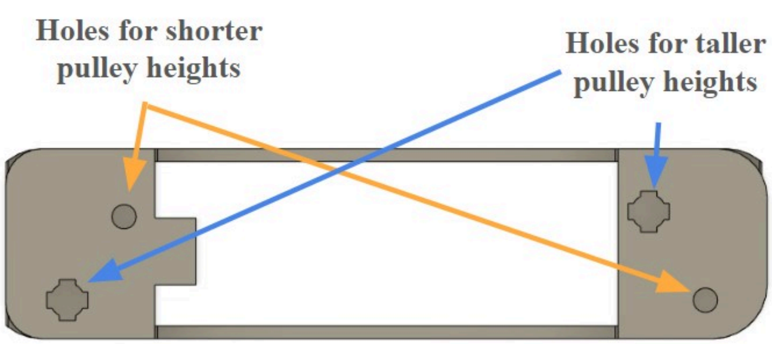



Figure 95: Hole Assignments for Gantry Pulleys

For the gantry pulleys to align with the taller heights mentioned, a removable spacer, depicted in Figure 96, that increases the gantry pulley height by 9.7 mm is added.

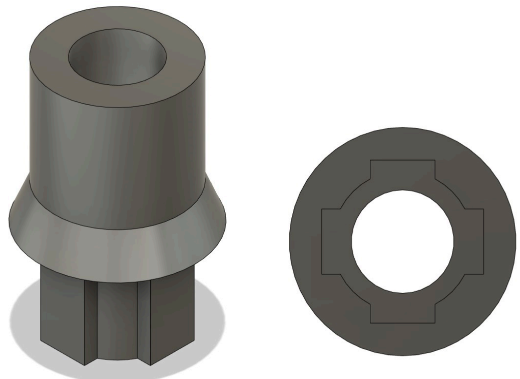


Figure 96: Removable Spacer Isometric View (left) and Bottom View (right)

The spacer has rectangular juts that fit into the rectangular slots seen in Figure 95. Once the spacer is pressed into the hole with slots, the pulley can be lined up with the center hole. The full configuration of gantry pulleys can be observed in Figure 97 below.

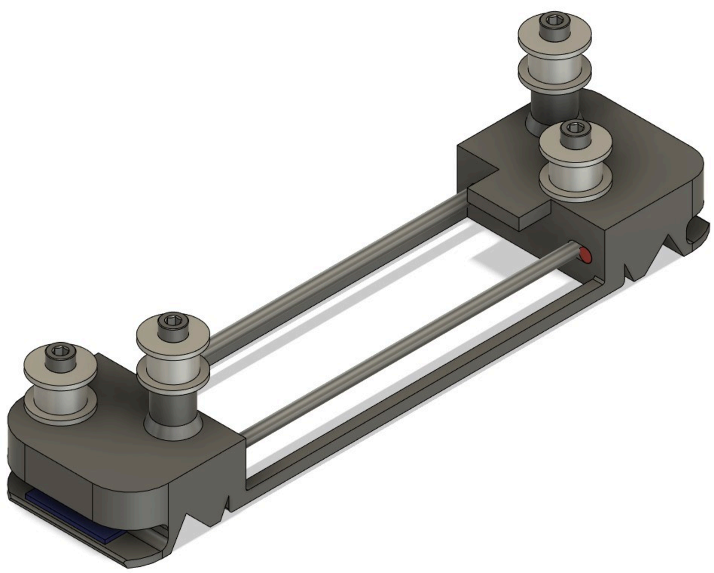


Figure 97: V-Groove Gantry with Pulleys and Spacers

The V-groove gantry's full assembly with the rods, bearings, removable spacers, rubber, limit switch, pulleys, belt tensioner, and bed holder is showcased in Figure 98 below.

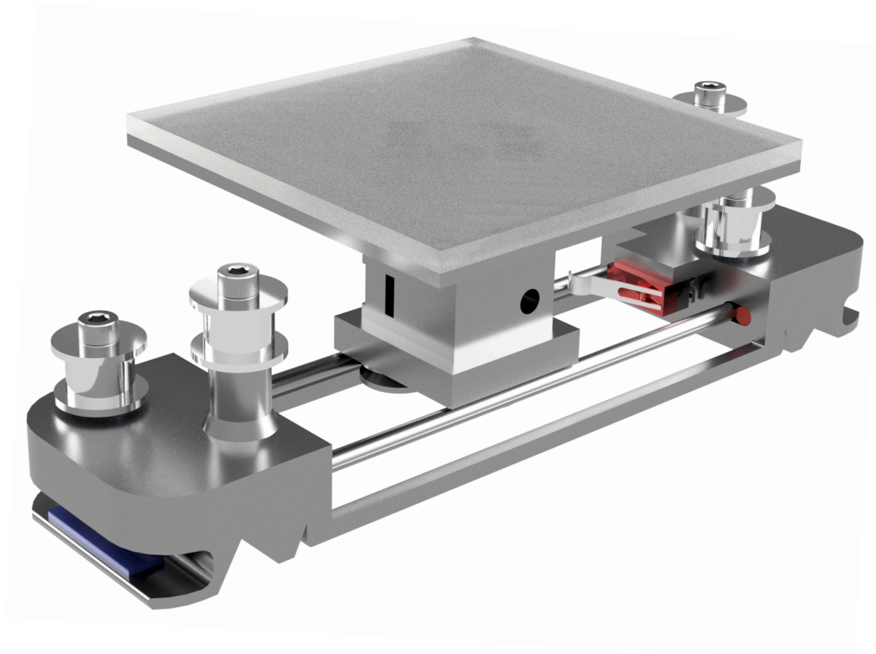


Figure 98: Isometric Rendering of the Fully Configured V-Groove Printer Gantry

### 3.4.2: V-Groove Gantry Movement

Though the method of moving the bed holder is different, the V-groove design shares the same base and method of moving the gantry as the Linear Rod design. The gantry has overhangs that move along two linear rods on each side. As mentioned in Section 3.3.1, the smaller, outer rods face a compressive force from a piece of rubber that acts as a preload. The gantry with Delrin attached to the top face of the overhang will travel along the linear rods of the base, thus allowing for movement of the gantry. The section profile of the gantry's overhang with Delrin traveling along the linear rod detailed in Figure 99 below.

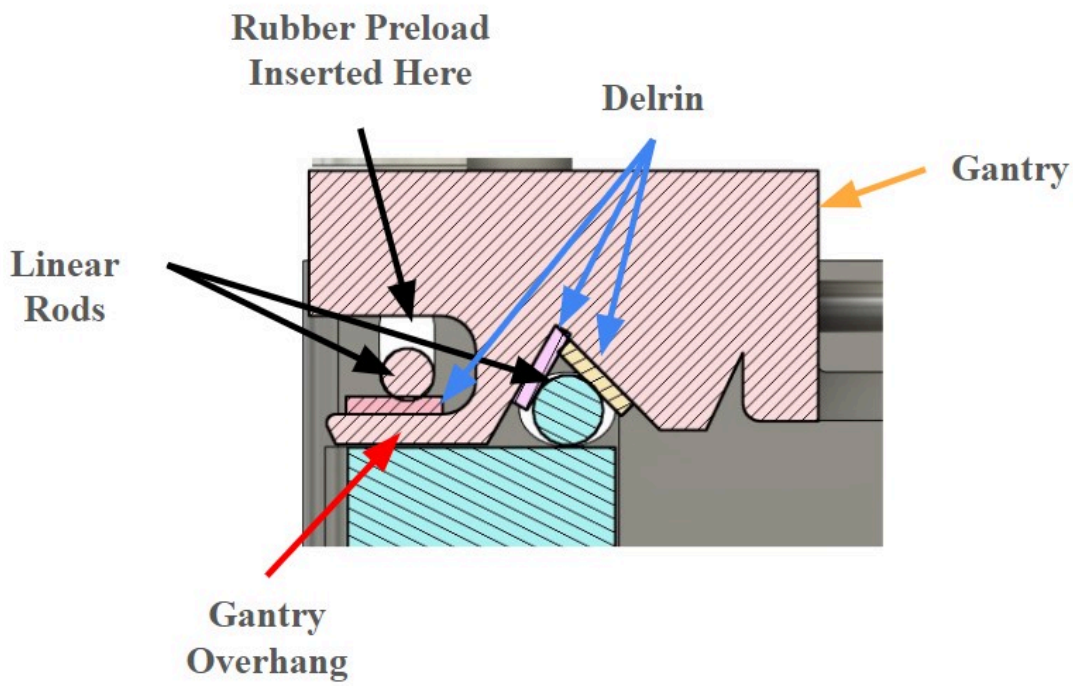



Figure 99: Gantry Rod Movement Section View

Due to the V-groove's gantry being slightly thicker than the Linear Rod's gantry, the Delrin used for less friction along the rods is thinner. Another size difference between the V-groove gantry and linear rod gantry that affects movement is the width. To accommodate the parallel rods used for the V-groove bearings and bed holder, the V-groove's gantry design is 37 mm, which is 7 mm wider than the linear rod's gantry. This allows for 7mm less in terms of the print volumes front to back motion, and should be considered in the pros and cons between the two designs.

Similar to the linear rod design, the pulleys attached to the gantry align with the pulleys attached to the motors, as well as the double stacked pulleys on the back corners of the base. As mentioned in the previous section, the gantry pulleys align with the bed holder's belt slots. With the movement of the bed holder and the gantry having aligning pulleys, the overall belt attachment should be functional for the CoreXY system. Figure 100 below showcases this pulley alignment.

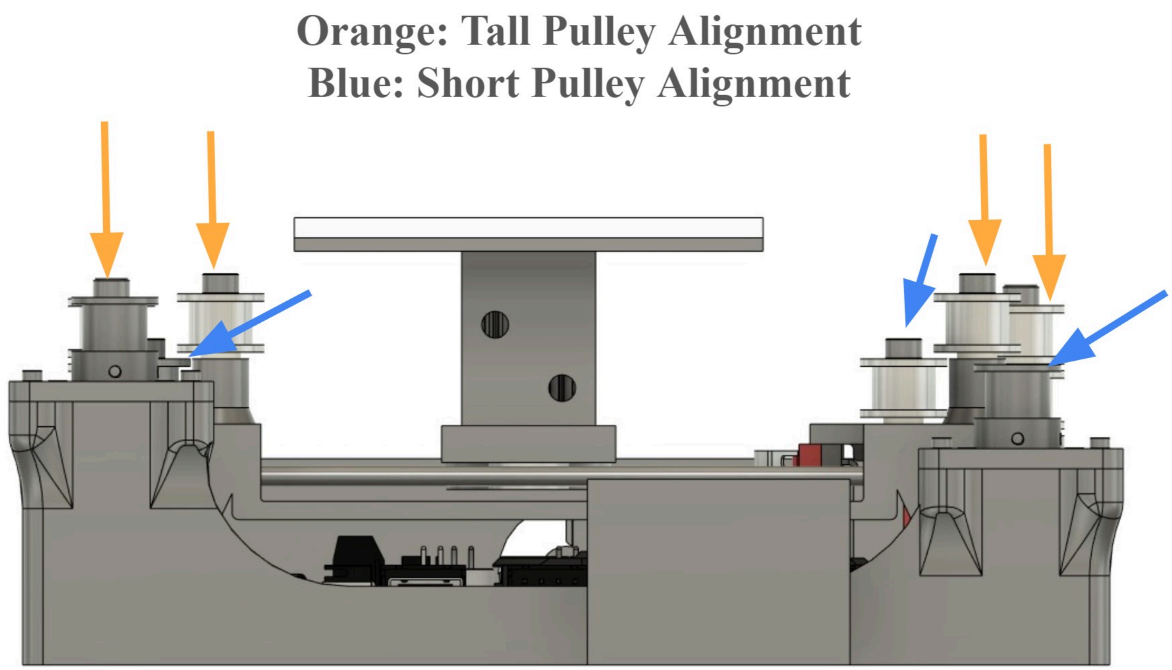



Figure 100: Overall V-Groove Pulley Alignment between the Gantry and Bed Holder Movements

### 3.4.3: V-Groove Full CAD Assembly

The full CAD of the V-groove, which includes the gantry and the base, can be seen in the isometric render in Figure 101 below.

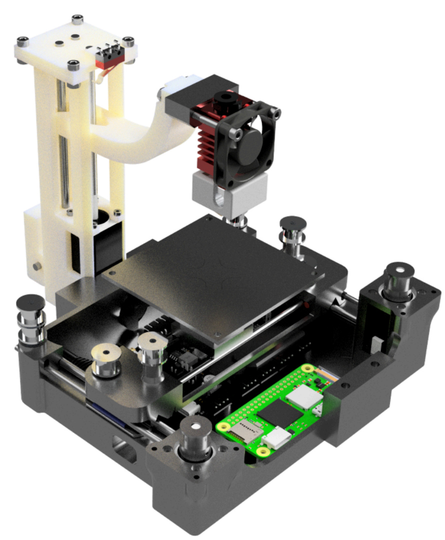


Figure 101: Isometric Render of the Full V-Groove CAD Assembly

### 3.4.4: V-Groove Final Prototype Assembly

The base has the same assembly as the Linear Rod version in Section 3.3.1, with the rubber preload, linear rods, motor covers, and electronics boards. The gantry is then aligned and inserted based on the designated rods, as seen in Figure 102 with the full assembly. Next, the belts are inserted through the slots of the bed holder and bed tensioner, and aligned with the pulleys in the CoreXY coordinate system. With that, everything for the X and Y-axes are assembled. The attachment of the Z-axis and electronic board is uniform amongst every printer. Attachment of the Z-axis is detailed in Section 3.1.3. Figure 102 also depicts the full assembly for X and Y-axis motion.

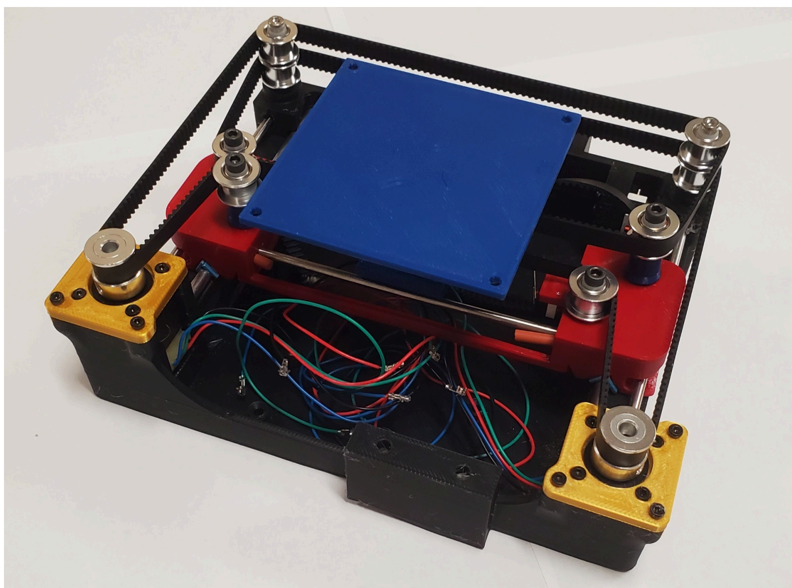


Figure 102: Full Assembly of the V-Groove Printer for X and Y-Axis Motion

Much like the linear rod design, the V-groove design does not feature the electronics board, as the team focused on delivering mechanical hardware that could replicate the CoreXY motion for this design. Electronics testing was not conducted on this system, but it does have the ability to house the same electronics as the linear guide rail design. Future testing with electronics is discussed in Section 7.1.

# Chapter 4: Analysis, Electronics, and Controls

## 4.1: Finite Element Analysis

### 4.1.1: Thermal Analysis - Hot End

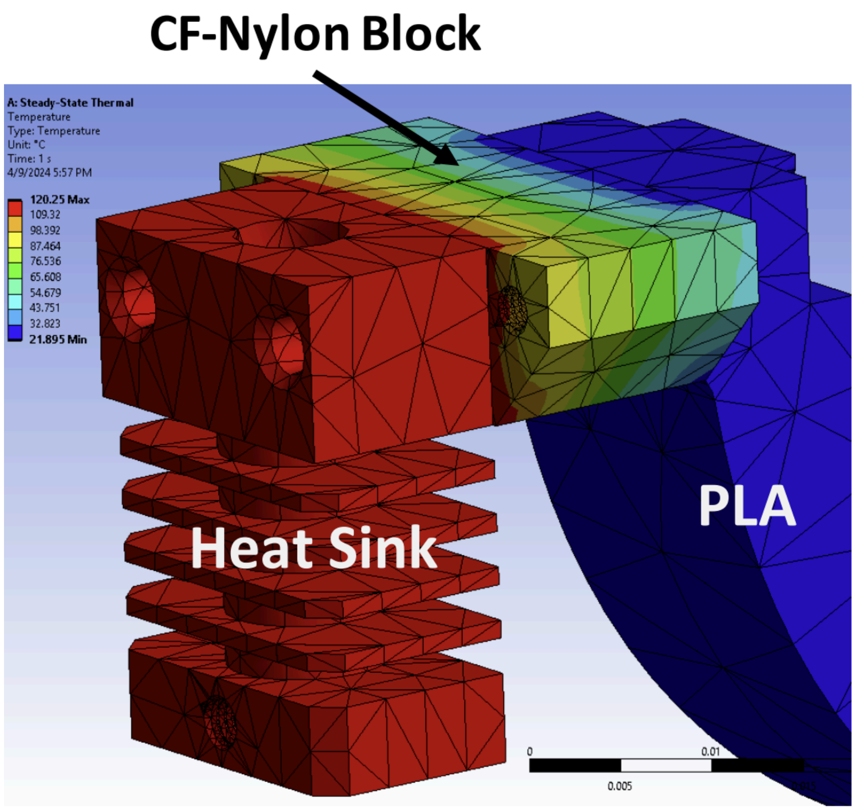



Figure 103: Ansys Simulation of the Heat Sink, Spacer Block, and Cantilever Arm

ANSYS was used to simulate heat flow through the heat sink as depicted in Figure 103 above. We found that the connecting block (blue) was unaffected, with an average temperature of 21.9°C. This is roughly ⅓ of the 60°C transition temperature and ensures that our parts will not either melt or warp when the hot end is at printing temperatures. This analysis validates that the CF-Nylon material would not fail during operation of the hot end when used as a spacer in direct contact with the heat sink.

## 4.2 Electronics Configuration

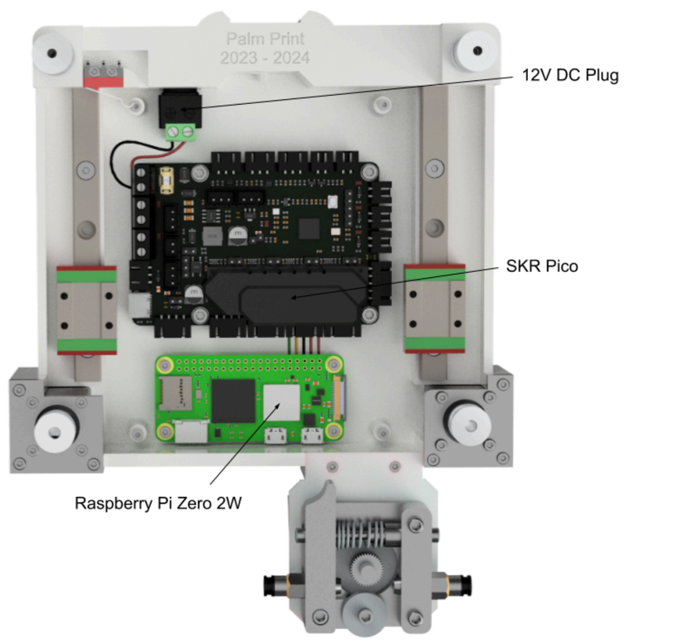



Figure 104: Electronics Configuration

The required wattage for the PSU is dependent on the sum of the individual components of the printer. Final electronics configuration is shown above in Figure 104. Palm Print does not use a heated bed, rather it uses a 30W hot end and three Nema 8 motors that draw approximately 3W/motor, bringing the minimum wattage for our power supply to 45W. Before accounting for the individual components, we attempted to use a 24W power supply commonly used for Arduino microcontrollers. Tested and final power supplies are shown in Figures 105 and 106 below.

Figure 105 (Left): Original 24W Power Supply Tested (Qanxun, 2024)
Figure 106 (Right): Common Power Supply (Alitove, 2024)

After connecting all the electronics, we attempted to preheat the hot end and found that the electronics would shut down when the thermistor read 105℃ - 110℃, indicating that our power supply was not powerful enough. We switched to a 12V 30A supply and everything worked as intended.

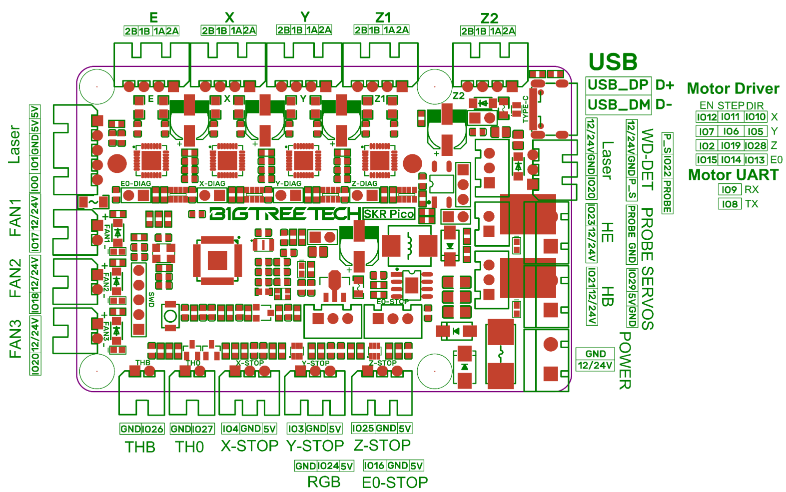



Figure 107: Wiring Diagram for SKR Pico (Voron v0.1, n.d.)

We used the Voron guide to wire the electronics into the SKR Pico, as shown in Figure 107 above. It defines the hardware and corresponding wiring sequence (Example Given: X End Stop: Pin 4, Ground, 5 Volts). Finally, a multimeter was used to verify that the wiring for the stepper motors was correct using a continuity test.

## 4.3 Firmware

Fluidd and Mainsail are the two main web interfaces used to communicate with Klipper. Palm Print features an SKR Pico microcontroller which runs Klipper firmware, a highly customizable open source firmware that allows us to control parameters needed for printing (Gharge, 2019). To access the Klipper firmware written on the Raspberry Pi Microcontroller, a local network - palmprint.local - was set up to allow for file exchange between a PC and the printer. We selected Mainsail for this project because it is easily accessible through the Raspberry Pi imager - a free tool that is used to write firmware to the Raspberry Pi's micro SD card.

We benchmarked Klipper based printers with similar build volumes to find similar source code that could be modified to work with our custom dimensions. The Voron V0, shown in Figure 108 below, was a major contributor to our Klipper code, as it has a build volume of 120mm x 120mm x 120mm - roughly twice as large as our build volume (Simons, 2023).


Figure 108: Voron V0 Printer (VoronDesign, 2023)

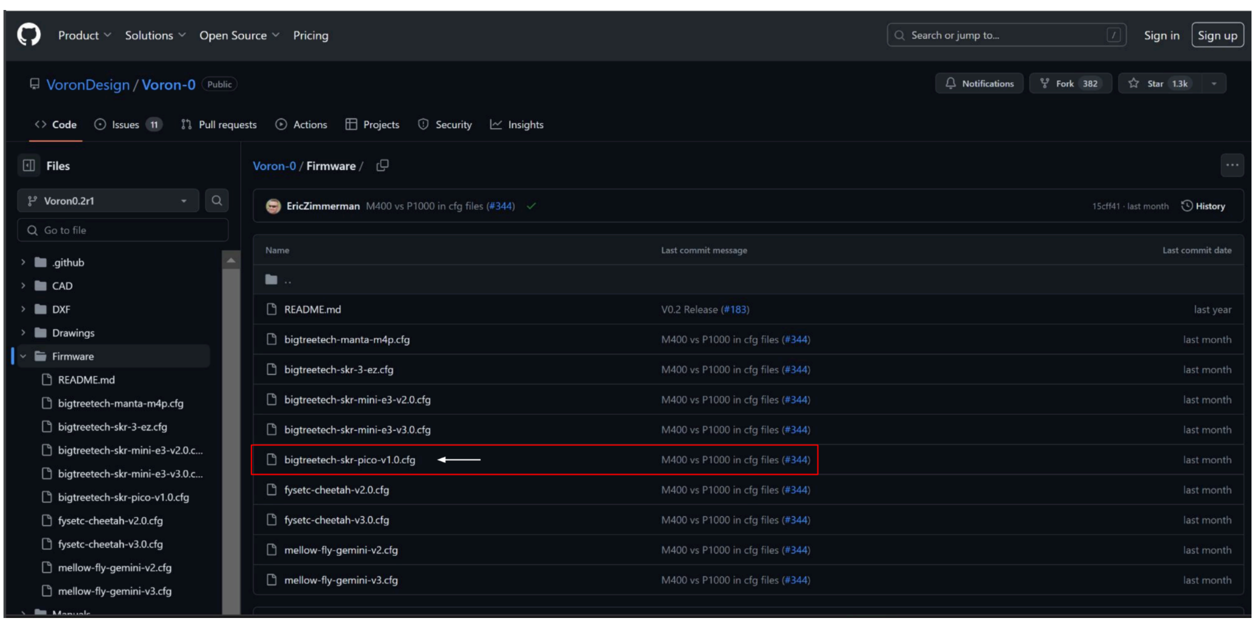



Figure 109: Voron V0 Github Page - SKR Pico Firmware (VoronDesign, 2023)

The file highlighted in red, in Figure 109 above, is the firmware file for the SKR Pico used in the Voron V0. Palm Print and the Voron printer share identical hardware setups but defer mechanically - with small changes such as the Voron using larger build volume,  a single limit switch for the Z-axis, no limit switch for X and Y directions (sensorless homing), heated build plate, and part cooling fan (VoronDesign, 2023).

## 4.4 Slicing Software

PrusaSlicer, shown in Figure 110 below, was selected as the slicing software for Palm Print because it is an open source, fully customizable software that allows for the creation of a custom printer profile. To create the printing profile, the software prompted us to enter dimensions for the X, Y, and Z directions (50mm x 50mm x 40mm) and the printing type (Klipper). This creates a custom 50mm x 50mm x 40mm build volume in the Prusa Software identical to Palm Print.

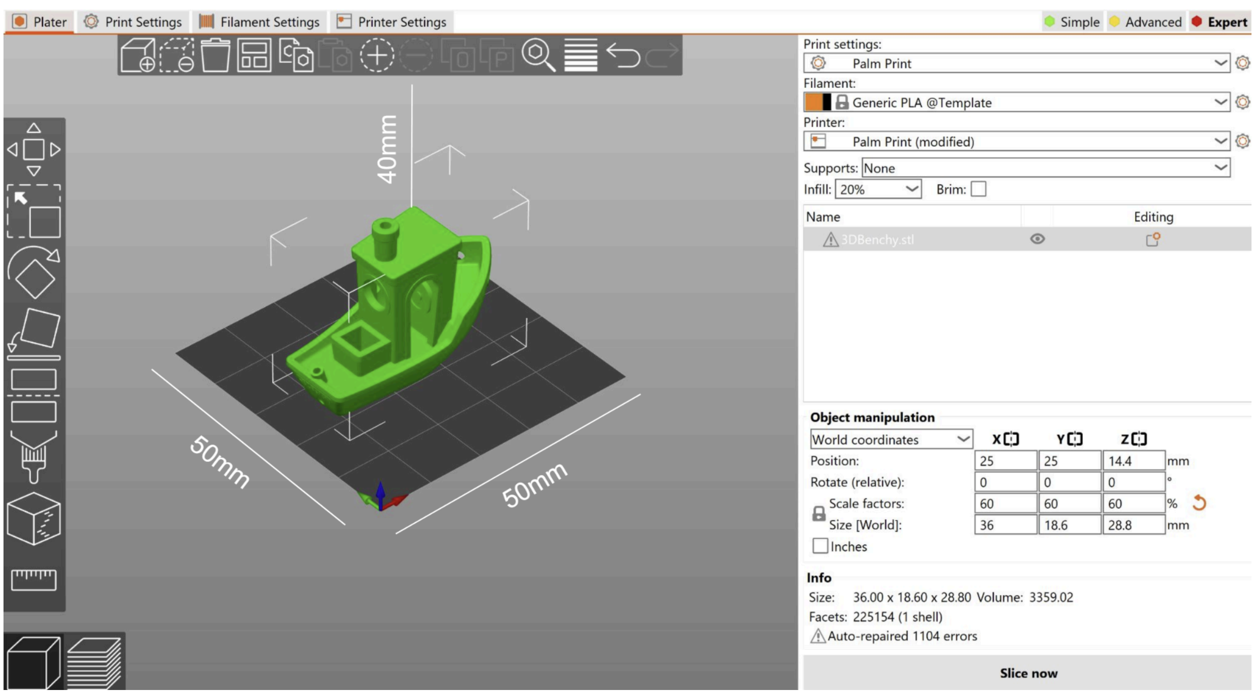



Figure 110: Benchy Boat Palm Print Example - PrusaSlicer

With the custom printing profile created in the PrusaSlicer, any 3D model can be imported into the slicer. After “slice now” is clicked, the G-Code file can be uploaded to our Klipper page, where printing automatically starts.

# Chapter 5: Safety

The team took measures to reduce the likelihood of injury during the use of Palm Print. Sharp edges and corners were reduced in the design as much as possible to prevent cuts and scratches during handling. The electronics were covered with a small sheet of acrylic to protect them, as well as the user from exposure to both the sharp edges and points on the electronic boards. This acrylic sheet also protects the power supply ports and cabling. The remaining wires not covered were encased in a professional-grade wiring harness, which acts as another barrier between the wiring and users. The cable ties used on the printer also had their sharp edges sanded down to prevent injury. Since the extruder cannot be enclosed without sacrificing the printer's functionality, the hot end should be marked as being hot while in operation, as coming into contact with it would result in serious burns. Additionally, warnings about pinch points on the printer's belts and pulleys should be labeled, since a finger placed between where the belts and pulleys interact would result in injury.

# Chapter 6: Conclusions

## 6.1: Palm Print Products

The team manufactured and assembled three prototypes of the CoreXY printer with a foldable Z-axis. With research and ideation dedicated to guaranteeing functionality within a small frame, we produced Palm Print to meet the customer's needs of portability and on-the-go FDM extrusion. The sizing and weight of each printer version can be seen in Table 3 below.

**Table 3: Printer Sizing and Weight**

| Printer Version | Size | Weight |
|---|---|---|
| Linear Rail | 16.7 x 25.7 x 15 cm | 1324 g |
| Linear Rod | 16.6 x 24.3 x 15 cm | 351 g* |
| V-Groove | 16.6 x 24.3 x 15 cm | 359 g* |

* Represents printers without the electronic boards and Z-axis weighed

Unlike versions from previous years, the three dimensional translation was achieved through the CoreXY coordinate system. This was accomplished for three unique systems with movement mechanisms widely seen in industry. The smooth motion can be attributed to the use of well-tensioned belts, belt alignment with the pulley and motor heights, and an effective electronic and software system. This was also the first year where the team's printer can both extrude filament and interpret G-code correctly.

## 6.2: Bill of Materials

With a budget of $1500, the team produced three prototypes of the Palm Print and remained well under the allotted capital with a total cost of $647.52. The complete Bill of Materials (BOM) is detailed in Table 4 and 5 below.

**Table 4: BOM - Palm Print**

| Item | Description | Quantity | Price | Total Cost |
|---|---|---|---|---|
| 1 | 10cm linear rail | 2 | $ 11.60 | $ 23.20 |
| 2 | 4mm 16T Pulley | 2 | $ 5.95 | $ 11.90 |
| 3 | Free Spinning Pulley | 2 | $ 7.99 | $ 15.98 |
| 4 | 4mm Pulley Shafts | 1 | $ 9.69 | $ 9.69 |
| 5 | 4x8x3mm bearings | 1 | $ 9.99 | $ 9.99 |
| 6 | 4mm x 25mm shaft | 1 | $ 7.99 | $ 7.99 |
| 7 | Nema 8 Motor | 6 | $ 24.45 | $ 146.70 |
| 8 | SKR Pico | 1 | $ 35.99 | $ 35.99 |
| 9 | Raspberry Pi 2W | 1 | $ 24.99 | $ 24.99 |
| 10 | 3x5x0.5mm washers | 1 | $ 6.49 | $ 6.49 |
| 11 | 3x6x1mm washers variety pack | 1 | $ 14.99 | $ 14.99 |
| 12 | 3x6x0.5mm washers | 1 | $ 5.99 | $ 5.99 |
| 13 | 3mm 16T pulley | 3 | $ 11.98 | $ 35.94 |
| 14 | 3mm to 4mm coupler | 3 | $ 6.99 | $ 20.97 |
| 15 | 1/2" dampers | 2 | $ 3.27 | $ 6.54 |
| 16 | JST XH kit | 1 | $ 9.58 | $ 9.58 |
| 17 | Crimper for JST XH | 1 | $ 25.99 | $ 25.99 |
| 18 | 25 Limit Switches | 1 | $ 6.99 | $ 6.99 |
| 19 | PETG - Orange | 1 | $ 21.99 | $ 21.99 |
| 20 | M2 Assorted | 1 | $ 9.99 | $ 9.99 |
| 21 | Threaded Inserts | 1 | $ 19.89 | $ 19.89 |
| 22 | Micro SD Card | 1 | $ 7.99 | $ 7.99 |
| 23 | Assorted Countersunk M3's | 1 | $ 12.99 | $ 12.99 |
| 24 | M3 x 26 | 1 | $ 6.99 | $ 6.99 |
| 25 | M3 x 8 | 1 | $ 7.86 | $ 7.86 |
| 26 | Ethernet Cable for TP link | 1 | $ 9.99 | $ 9.99 |

| | | | | |
|---|---|---|---|---|
| 27 | TP Link Wifi Extender | 1 | $ 16.96 | $ 16.96 |
| 28 | V Groove Bearing | 1 | $ 8.29 | $ 8.29 |
| 29 | 30mm Fan | 1 | $ 8.49 | $ 8.49 |
| 30 | Creality Glass Bed | 1 | $ 11.99 | $ 11.99 |
| 31 | Creality Hotend | 1 | $ 16.99 | $ 16.99 |
| 32 | Sunlu PLA - Black | 1 | $ 13.99 | $ 13.99 |
| 33 | Esun PETG | 1 | $ 25.99 | $ 25.99 |
| 34 | Nema 17 | 1 | $ 7.99 | $ 7.99 |
| 35 | Bowden Extruder | 1 | $ 9.99 | $ 9.99 |
| 36 | Anti Backlash Nuts | 1 | $ 7.89 | $ 7.89 |
| 37 | Nema 8 w. 4mm x 100mm Lead Screw | 1 | $ 24.45 | $ 24.45 |

**Table 5: Palm Print Budget**

| | |
|---|---|
| Total Spent | $647.52 |
| Budget | $1,500 |
| Percent of Budget Remaining | 56.84% |

Separating the total BOM amongst each printer, the cost of each Palm Print version can be observed in Table 6 below. It should be noted that each version includes the cost of the Z-axis, which adds $55.03 to the cost of each prototype version. This table also includes a potential sale price and the profit margin from selling a single unit.

**Table 6: Palm Print Cost and Pricing**

| Prototype Version | Cost | Sale Price | Profit |
|---|---|---|---|
| Linear Rail | $249.98 | $299.99 | $50.01 (16.7%) |
| Linear Rod | $193.11 | $249.99 | $56.88 (22.8%) |
| V-Groove | $191.96 | $249.99 | $58.03 (23.2%) |

# Chapter 7: Recommendations

## Recommendation 1: Cyclical Testing of the CoreXY Systems

With three distinct Palm Print prototypes produced, cyclic testing is recommended to analyze the lifetime wear of each version. All of the mechanisms used to produce 3 dimensional motion are viable and seen within industry, but there was not enough time to conduct several printing tests for each version. Testing for lifetime wear would be beneficial to determine the best design for long term, portable FDM printing. Factors such as material stress, belt friction and wear, and electronic stability can all be measured to help verify if a design can maintain its functionality after hundreds or thousands of prints. After these tests are conducted, complications of each printer can be assessed, and the best overall version of the CoreXY systems can be determined. The printer that is chosen would then have the entire focus of future teams and become the initial product that is sold to customers.

## Recommendation 2: Motor Selection

As seen in the total BOM, the NEMA 8 Motors accounted for 26.4% of the spent budget. These motors were the smallest motors with the required torques the team could find. We recommend future Palm Print teams to research a possible alternative to the NEMA 8 with a similar torque output. This alternative may sacrifice the overall size with a larger motor, but the potential for larger sales due to the lower motor price must be considered. If Palm Print is sold to customers, then the problem may be solved through bulk purchasing, as there may be special pricing due to the quantity. This method is harder to determine, as distributors can have different pricings for bulk purchasing, with some being more expensive than others. This cost decrease allows for Palm Print to become a viable option for a wider range of customers.

## Recommendation 3: Produce a Protective Case for Travel

With the intentions of a transportable printing device, Palm Print must have a protective case to protect the printer from any damages acquired from travel. Carrying Palm Print in a backpack or any form of luggage puts the printer at risk of breaking, components becoming missing, or scuffing. Components such as the Z-axis, belts, and bed holder are at particular risk of damage, as those are systems that could easily deform, detach, or misalign from the overall system. A specialized carrying case that houses the printer in its folded state would be an ideal measure to help prevent any damages incurred from travel.

# Chapter 8: Broader Impacts

## 8.1: Engineering Ethics for Palm Print

In the making of Palm Print, the team ensured that the research, ideation, design, manufacturing, and analysis either abided by or enforced the ethical practices detailed by the American Society of Mechanical Engineers (ASME) and National Society of Professional Engineers (NPSE). Our research phase focused on gaining a true understanding of the components required to make a small scale 3D printing product. With Palm Print being a product that is sold to consumers, companies, and institutions, our ideation phase delved into the needs and wants of the customer. We were able to optimize aspects of the Palm Print such as the size, components, kinematic system, and folding mechanisms for transportation. This was done through the mind maps, reverse engineering, Pugh Matrices, and circle sketches mentioned in Chapter 2. We want Palm Print to be a new form of additive manufacturing that is beneficial to all who use it.

## 8.2: Global Impact

Palm Print is primarily directed towards students, as well as design and manufacturing engineers. Palm Print can reach younger students through a school's engineering activities and projects. The Palm Print was produced to be an entry level device into additive manufacturing. It is something that a student can take with them to continue iterating, designing, and prototyping. Exposing students to engineering concepts early on can help encourage more curiosity and insight into the field. Palm Print also helps design and manufacturing engineers create small scale parts for their intended designs. This can be particularly useful in industries that require their components to be smaller in size. An example of this would be the speaker industry. With the size of speakers becoming smaller, optimal manufacturing of these components are required. Another such industry would be in the biomedical field, where smaller, more organically-shaped parts are common. Having a smaller printer capable of manufacturing these types of parts onsite would be incredibly useful and may significantly reduce wait times to receive such parts.

## 8.3: Environmental Impact

With Palm Print's small dimensions, the required consumption of energy and plastic is far below other 3D printers on the market. The minimum voltage requirement for Palm Print is 12V which is optimal for small scale prints, as printing those parts on a standard 3D Printer on the market will use more power with its larger components.

Another environmental consideration is the filament material the Palm Print can extrude and is primarily made of. With no heat bed equipped in any version of the Palm Print, the only extrudable filament material is PLA. Unlike filaments such as ABS, PLA can be recycled with relative ease. Since PLA is derived from corn, the products produced with Palm Print can be recycled and created into either a new spool of filament or sent to a recycle center for others to recycle into new rolls (West, 2020). Additionally, the device is primarily constructed out of the same material, which makes it largely recyclable itself down the road.

## 8.4 Codes and Standards

Abiding by the codes and standards as defined by the American Society of Mechanical Engineers (ASME) and the National Society of Professional Engineers (NSPE) not only leads to a more ergonomic and usable design for a product, but it also prioritizes the public and the consumer over other more selfish considerations. This ultimately prevents malpractice in engineering, which whether knowingly or unknowingly can cause catastrophes or otherwise ineffective products to be brought to the market. During the development of Palm Print, strategies were employed to both abide by and hold the standards as paramount.

Above all, the development of Palm Print was done with the safety of the consumer in mind. During the design and development of Palm Print, hazards were reduced as much as reasonably possible (such as sharp edges and exposed electrical connections). Given the nature of the product, there are some inherent hazards that have been outlined in Chapter 5 for transparency. Throughout the design process, the use cases and consumer were kept in mind, adhering to this critical standard outlined in the ASME and NSPE codes.

The vast majority of the fasteners used in the assembly of Palm Print are standard metric fasteners. This allows the overall cost of fasteners to be reduced while allowing them to be more easily available should replacements need to be made during the product's lifetime. Having proprietary or non-standard fasteners especially is largely wasteful and impractical, driving the cost of a comparable product up while hindering access to replacement parts for maintenance in the future. Where applicable, the serviceability of Palm Print was considered during the design process.

## 8.5 Economic Factors

The intent of Palm Print was to make it reasonably accessible to the general public, keeping the final sale price equal to or below $300 for a collapsible, portable 3-D printer. Employing techniques such as the use of standard hardware, inexpensive materials, and limiting the total amount of material required allowed the device to adhere to this goal. Most of the components that make up Palm Print are easily accessible via either Amazon or other online distributors such as StepperOnline. As mentioned in Section 4.2, Palm Print only requires 45W of power. Power consumption for printing small components on Palm Print is less than a larger printer, saving users money on electricity bills in the long term.

# Appendices

**Table 7: Linear Rail BOM**

| Description | Items per pack | Item Cost | Unit Cost | Quantity Used | Total Cost per printer |
|---|---|---|---|---|---|
| 10cm Linear Rail | 1 | $ 11.60 | $ 11.60 | 2 | $ 23.20 |
| 4mm 16T Pulleys | 5 | $ 5.99 | $ 1.20 | 2 | $ 2.40 |
| 4mm Pulley Shafts | 5 | $ 9.69 | $ 1.94 | 2 | $ 3.88 |
| Nema 8 Motor | 1 | $ 24.45 | $ 24.45 | 3 | $ 73.35 |
| SKR Pico | 1 | $ 35.99 | $ 35.99 | 1 | $ 35.99 |
| Raspberry Pi 2W | 1 | $ 24.99 | $ 24.99 | 1 | $ 24.99 |
| 3x6x1mm washers variety pack | 550 | $ 14.99 | $ 0.03 | 18 | $ 0.49 |
| 3mm 16T pulley | 10 | $ 11.98 | $ 1.20 | 8 | $ 9.58 |
| 1/2" Dampers | 12 | $ 3.27 | $ 0.27 | 6 | $ 1.64 |
| JST XH Connectors | 460 | $ 9.58 | $ 0.02 | 9 | $ 0.19 |
| Limit Switches | 25 | $ 6.99 | $ 0.28 | 3 | $ 0.84 |
| M2 Assorted Bolts | 660 | $ 9.99 | $ 0.02 | 20 | $ 0.30 |
| M3 x 26 Bolts | 40 | $ 6.99 | $ 0.17 | 2 | $ 0.35 |
| Threaded Inserts | 460 | $ 19.89 | $ 0.04 | 30 | $ 1.30 |
| Micro SD Card | 1 | $ 7.99 | $ 7.99 | 1 | $ 7.99 |
| Assorted Countersunk M3's | 260 | $ 12.99 | $ 0.05 | 10 | $ 0.50 |
| 30mm Fan | 4 | $ 8.49 | $ 2.12 | 1 | $ 2.12 |
| Creality Hotend | 1 | $ 16.99 | $ 16.99 | 1 | $ 16.99 |
| Assorted Countersunk M3's | 260 | $ 12.99 | $ 0.05 | 10 | $ 0.50 |
| M3 x 8 Bolts | 100 | $ 7.86 | $ 0.08 | 4 | $ 0.31 |
| 12V DC Power Plug | 4 | $ 5.20 | $ 1.30 | 1 | $ 1.30 |
| Sunlu PLA - Black | 1 | $ 13.99 | $ 13.99 | 0.237 | $ 3.32 |
| Nema 17 | 1 | $ 7.99 | $ 7.99 | 1 | $ 7.99 |
| Bowden Extruder | 1 | $ 9.99 | $ 9.99 | 1 | $ 9.99 |
| Creality Glass Bed | 1 | $ 11.99 | $ 11.99 | 1 | $ 11.99 |
| 4mm x 25mm shaft | 2 | $ 7.99 | $ 4.00 | 1 | $ 4.00 |
| GT2 Belt | 1 | $ 8.99 | $ 8.99 | 0.5 | $ 4.50 |
| | | | | **Total** | **$ 249.98** |

**Table 8: Linear Rail BOM**

| Description | Items per pack | Item Cost | Unit Cost | Quantity Used | Total Cost per printer |
|---|---|---|---|---|---|
| 4mm 16T Pulleys | 5 | $ 5.99 | $ 1.20 | 2 | $ 2.40 |
| 4mm Pulley Shafts | 5 | $ 9.69 | $ 1.94 | 2 | $ 3.88 |
| Nema 8 Motor | 1 | $ 24.45 | $ 24.45 | 3 | $ 73.35 |
| Arduino Mega 2560 | 1 | $ 35.99 | $ 35.99 | 1 | $ 35.99 |
| 3x6x1mm washers variety pack | 550 | $ 14.99 | $ 0.03 | 18 | $ 0.49 |
| 3mm 16T pulley | 10 | $ 11.98 | $ 1.20 | 8 | $ 9.58 |
| 1/2" Dampers | 12 | $ 3.27 | $ 0.27 | 6 | $ 1.64 |
| Limit Switches | 25 | $ 6.99 | $ 0.28 | 3 | $ 0.84 |
| M2 Assorted Bolts | 660 | $ 9.99 | $ 0.02 | 20 | $ 0.30 |
| M3 x 26 Bolts | 40 | $ 6.99 | $ 0.17 | 2 | $ 0.35 |
| Threaded Inserts | 460 | $ 19.89 | $ 0.04 | 30 | $ 1.30 |
| 30mm Fan | 4 | $ 8.49 | $ 2.12 | 1 | $ 2.12 |
| Creality Hotend | 1 | $ 16.99 | $ 16.99 | 1 | $ 16.99 |
| Assorted Countersunk M3's | 260 | $ 12.99 | $ 0.05 | 10 | $ 0.50 |
| M3 x 8 Bolts | 100 | $ 7.86 | $ 0.08 | 4 | $ 0.31 |
| 12V DC Power Plug | 4 | $ 5.20 | $ 1.30 | 1 | $ 1.30 |
| Sunlu PLA - Black | 1 | $ 13.99 | $ 13.99 | 0.237 | $ 3.32 |
| Nema 17 | 1 | $ 7.99 | $ 7.99 | 1 | $ 7.99 |
| Bowden Extruder | 1 | $ 9.99 | $ 9.99 | 1 | $ 9.99 |
| Creality Glass Bed | 1 | $ 11.99 | $ 11.99 | 1 | $ 11.99 |
| 4mm x 25mm shaft | 2 | $ 7.99 | $ 4.00 | 1 | $ 4.00 |
| GT2 Belt | 1 | $8.99 | $ 8.99 | 0.5 | $ 4.50 |
| | | | | **Total** | **$ 193.11** |

**Table 9: V-Groove Bearing BOM**

| Description | Items per pack | Item Cost | Unit Cost | Quantity Used | Total Cost per printer |
|---|---|---|---|---|---|
| 4mm 16T Pulleys | 5 | $ 5.99 | $ 1.20 | 2 | $ 2.40 |
| 4mm Pulley Shafts | 5 | $ 9.69 | $ 1.94 | 2 | $ 3.88 |
| Nema 8 Motor | 1 | $ 24.45 | $ 24.45 | 3 | $ 73.35 |
| Arduino Mega 2560 | 1 | $ 35.99 | $ 35.99 | 1 | $ 35.99 |
| 3x6x1mm washers variety pack | 550 | $ 14.99 | $ 0.03 | 18 | $ 0.49 |
| 3mm 16T pulley | 10 | $ 11.98 | $ 1.20 | 8 | $ 9.58 |
| 1/2" Dampers | 12 | $ 3.27 | $ 0.27 | 6 | $ 1.64 |
| Limit Switches | 25 | $ 6.99 | $ 0.28 | 3 | $ 0.84 |
| M2 Assorted Bolts | 660 | $ 9.99 | $ 0.02 | 20 | $ 0.30 |
| M3 x 26 Bolts | 40 | $ 6.99 | $ 0.17 | 2 | $ 0.35 |
| Threaded Inserts | 460 | $ 19.89 | $ 0.04 | 30 | $ 1.30 |
| 30mm Fan | 4 | $ 8.49 | $ 2.12 | 1 | $ 2.12 |
| Creality Hotend | 1 | $ 16.99 | $ 16.99 | 1 | $ 16.99 |
| Assorted Countersunk M3's | 260 | $ 12.99 | $ 0.05 | 10 | $ 0.50 |
| M3 x 8 Bolts | 100 | $ 7.86 | $ 0.08 | 4 | $ 0.31 |
| 12V DC Power Plug | 4 | $ 5.20 | $ 1.30 | 1 | $ 1.30 |
| Sunlu PLA - Black | 1 | $ 13.99 | $ 13.99 | 0.237 | $ 3.32 |
| Nema 17 | 1 | $ 7.99 | $ 7.99 | 1 | $ 7.99 |
| Bowden Extruder | 1 | $ 9.99 | $ 9.99 | 1 | $ 9.99 |
| Creality Glass Bed | 1 | $ 11.99 | $ 11.99 | 1 | $ 11.99 |
| 4mm x 25mm shaft | 2 | $ 7.99 | $ 4.00 | 1 | $ 4.00 |
| GT2 Belt | 1 | $8.99 | $ 8.99 | 0.5 | $ 4.50 |
| V Groove Bearing | 20 | $8.29 | $ 0.41 | 3 | $ 1.24 |
| | | | | **Total** | **$ 191.96** |

**Table 10: Z-Axis BOM**

| Description | Items per pack | Item Cost | Unit Cost | Quantity Used | Total Cost per printer |
|---|---|---|---|---|---|
| 4mm Pulley Shafts | 5 | $ 9.69 | $ 1.94 | 2 | $ 3.88 |
| Nema 8 w. 4mm x 100mm Lead Screw | 1 | $ 24.45 | $ 24.45 | 1 | $ 24.45 |
| Creality Hotend | 1 | $ 16.99 | $ 16.99 | 1 | $ 16.99 |
| Limit Switch | 25 | $ 6.99 | $ 0.28 | 1 | $ 0.28 |
| M3 x 8 | 100 | $ 7.86 | $ 0.08 | 4 | $ 0.31 |
| 1/2" Dampers | 12 | $ 3.27 | $ 0.27 | 1 | $ 0.27 |
| M2 Assorted Bolts | 660 | $ 9.99 | $ 0.02 | 4 | $ 0.06 |
| M3 x 26 Bolts | 40 | $ 6.99 | $ 0.17 | 2 | $ 0.35 |
| M3 x 26 Bolts | 40 | $ 6.99 | $ 0.17 | 2 | $ 0.35 |
| 30mm Fan | 4 | $ 8.49 | $ 2.12 | 1 | $ 2.12 |
| Esun PETG | 1 | $ 25.99 | $ 25.99 | 0.073 | $ 1.90 |
| 4mm x 25mm shaft | 2 | $ 7.99 | $ 4.00 | 1 | $ 4.00 |
| Anti Backlash Nuts | 2 | $ 7.89 | $ 3.95 | 1 | $ 3.95 |
| | | | | **Total** | **$ 55.03** |

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