Palm Print: Portable 3D Printer

A Major Qualifying Project

Submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfilment of the requirements for the

Degree of Bachelor of Science

in Mechanical & Materials Engineering

Submitted By:

Igor De Moraes: Mechanical & Materials Engineering

Alvaro Gonzalez Garcia: Mechanical & Materials Engineering

Nathan Morin: Mechanical & Materials Engineering

Ana Paula Navarro Aguayo: Mechanical & Materials Engineering

April 28, 2022

Completed under the advisement and approval of:

Project Advisor:

Professor Joe Stabile: Mechanical & Materials Engineering

WORCESTER POLYTECHNIC INSTITUTE

Acknowledgements

In memoriam of our beloved friend and teammate, Nathan Morin. All the great memories we shared will forever be remembered. Thank you for how much you helped us; you were a brilliant leader. We are so thankful for all the amazing memories and great laughs.

Abstract

Additive manufacturing (AM) is the industrial production name for 3D printing, a computer-controlled process that creates three dimensional objects by depositing materials, usually in layers. AM technologies have enabled the production of end-use products at low costs, faster lead times, and less environmental impact, with a user-friendly interface. Creating an affordable and portable 3D printer would allow users, especially students, to manufacture prototypes utilized for a wide range of small projects and applications. Using Autodesk Fusion360, a Computer-Aided Design (CAD) Software, and 3D printers to design and test different prototypes. The Palm Print: Portable 3D Printer was constructed for under $150. The 3D printer has the capability of printing a 2x2x1.8" build volume using PLA (Polylactic Acid) plastic filament. The Palm Print: Portable 3D Printer is functional but leads to some improvements that could be made to increase the performance of the product and allow for a marketable product.

Table of Contents

List of Figures

List of Tables

1. Introduction

Over the last couple decades, there have been many innovations and discoveries relevant to Additive Manufacturing, one of the most well-known is 3D printing. Fusion Deposition Modeling (FDM) is the printing process most generally referred to when 3D printing. Currently, 3D printers can serve as a tool for construction and shop workers, or even artists and designers. The commercialization of the printers has led to a wide range of prices, sizes and replaceable part which makes owning and maintaining a printer accessible for a wide range of product users.

1.1 Goals

The main goal of the project is to design and create a portable and inexpensive 3D printer to be used for manufacturing small parts and prototypes and that could be easily assembled and disassembled or open and closed. The target product cost is less than $150, and the printer must be able to accommodate for a build plate of at least 2” x 2” in area, while trying to decrease the size of the previous design of the Palm Print: Portable 3D Printer.

Designing a printer that meets the given design goals, would allow for a cheap 3D printer that could be bought in bulk and used for educational purposes in demonstrating the manufacturing of end-use products at low production costs. This product would make it accessible for everyone to gain familiarity with 3D printers, the growing technology and manufacturing processes.

2. Background

Understanding Fused Deposition Modeling is critical in understanding how a 3D printers functions, especially when it comes to making sure the printer is operating properly. A 3D printer does not require many parts to function. The increases in part count are typically caused by the travel mechanism and how the hot end is being moved to the desired location for layer deposition. Typically, the main parts of a 3D printer will include the housing, print bed, filament, extruder, motors, and microcontroller but could differ in the type of movement mechanisms and software.

2.1 What is a 3D Printer

AM, also known as additive manufacturing or rapid prototyping (RP), 3D printing has become bigger and bigger as the technology progresses, due to the fast-manufacturing time and low-cost production. AM was originally brought to the public by Charles Hull, an Engineering Physics major from The University of Colorado, in the 1980s [26]. Seeing the lengthy and costly process of prototyping, Hull set out to create an innovative new technology for industrial fabrication. As this technology developed, it became a way to shorten manufacturing time, increase prototyping frequency, and cut costs of testing products enormously. Before AM, parts were created by a technique called subtractive manufacturing, which removed unnecessary material from a full block of stock. Additive manufacturing, on the other hand, creates parts by meting material and printing it layer by layer, creating ultimately no waste.

The 3D printing process begins in a computer-aided design (CAD) software. Any 3D modeling program, such as Dassault Systemes SolidWorks and Autodesk Fusion 360, which allow the user to digitally create a 3D model of any object. Once the CAD design for the part is done, the file model is then transferred to a stereolithography or .STL file. STL files, introduced by Hull in 1988, describe the surface geometry of the object, color, and allow communication between the 3D printer and the 3D modeling software. The .STL file is interpreted by the 3D printer which then creates a G-file via a slicer program. The G-file divides the 3D file into a sequence of 2D cross-sections, which the printer will print layer by layer to create the originally designed 3D model. After all the information is processed the 3D printer heats up and gets ready to start printing each layer [26].

2.1.1 Fused Deposition Modeling

Fused Deposition Modeling is a type of material extrusion 3D printing process. FDM is the process of a filament being fed through an extruder and heated by a hot-end before depositing the melted material in layers on the build surface to constructed the desired geometries. When dealing with complex part geometries, this process has the capabilities of also adding support layers to properly deposit each main part layer. This process mainly focuses on using plastics as filaments, and the properties of the finished product typically cannot be altered [7].

2.2 Components used for a 3D Printer

The main components of a 3D printer are the housing, filament, print bed, extruder, motors, and controller board. However, there are many other smaller components that will impact the performance of the printer and quality of the print. These components can include pullies, lead screws, limit switches, rails, screws, and springs [2].

2.2.1 Filaments

The properties of a completed print are determined by the filament being used for printing. The filament is the main component responsible to having an impact on strength, elasticity, surface finish, and color of the print being made. However, since the properties of the part are determined by the filament, this also means that some changes need to be made to the printer to successfully print when using a different material. This typically means a change to the nozzle and print bed temperature so the hot-end can properly melt the materials and the materials will adhere, but could also mean a change in the feed speed or filament diameter. Most commonly filaments are a type of plastic, but there are some printers with capabilities of printing metals and ceramics. Table 1 includes a list of common consumer 3D printer filaments [18].

Table 1: Table of filament that be used for 3D printing [18]

Material Name	Abbreviation	Strength	Flexibility	Durability	Print Temperature (°C)	Bed Temperature (°C)
Polylactic Acid	PLA	High	Low	Medium	180-230	20-60 (Not needed)
Acrylonitrile Butadiene Styrene	ABS	High	Medium	High	210-250	80-100
Polyethylene Terephthalate	PET (PETG, PETT)	High	Medium	High	220-250	50-75
Thermoplastic Elastomers	TPE (TPC, TPU)	Medium	Very High	Very High	210-230	30-60 (Not needed)
Nylon	--	High	High	High	240-260	70-100
Polycarbonate	PC	Very High	Medium	Very High	270-310	90-110

As an attempt to keep the total product cost low, we will be using parts that are made to print PLA, as the parts are the most common, and retail at a lower price point. However, some other materials may be compatible with the chosen parts.

2.2.2 Enclosure

3D printer enclosures have several different functions. One of its main functions is insulating print area, especially when it is a heated print area. They are also used for protecting the printer from anything in the environment around it that may affect the printing process [31]. Some benefits of using an enclosure are, protecting the prints from drafts as well as changing temperatures, protecting the 3D printer from dust, trapping fumes emitted in the printing room and if the enclosure has metal, it enhances fire safety [31]. Enclosures can vary in shapes, sizes, and material. Depending on the 3D printers need, these characteristics can be changed. However, an enclosure's functionality has nothing to do with its size or shape if it accomplishes its purpose [31].

2.2.3 Print Bed

The print bed is one of the most important parts of the printer. The bed is where all the layers of filament will be deposited, and it is also the part that will determine how big of a print you will be able to produce. Typically, there is an option to heat the print bed to help with adhesion for many filament materials, but there are some types of materials that do not need a heated print bed. The print bed is also what will be leveled prior to every print to make sure the that the filament is being deposited on a flat even surface. Table 2 shows the different materials that a print bed can be made of, and the materials that can be printed on the given print bed [43].

Table 2: Table of different print bed materials and what can be printed on the print bed [43]

Print bed material	Materials that can be printed
Glass	• PLA
	• ABS
	• PETG
	• TPU
	• Nylon
Acrylic	• PLA
Spring Steel PEI	• PLA
	• ABS
	• PETG
	• TPU
	• Nylon
G10	• PLA
	• ABS
	• ASA
	• PET
	• PETG
	• TPU
	• Nylon
Polypropylene (PP)	• PLA
	• ABS
	• PETG
	• PC
	• TPU
	• Nylon
	• PP
Kapton Tape	• PLA
	• ABS
	• PETG

2.2.4 Extruder

The extruder is in responsible for holding the filament in place and controlling the amount that is fed into a hot-end. It is composed of two main components: the driver or cold end, and the hot end. The driver feeds the filament to the hot end through a gear system hooked up to a stepper motor. The hot end heats up the material until its ready to be printed. Then the extruder, being one of the most important components of the FDM 3D printers, must be properly set up for the best results. There are two types of extruders: Direct Drive and Bowden Extruders [38].

Direct Extruder

A direct extruder's cold end is placed closer to the hot end. Sometimes attached to the frame of the 3D printer or to the top of the hot end, away from the hot components as shown in Figure 1. Since the position of the extruder is much closer to the hot end it makes the system simpler and less likely to fail. This design minimizes the distance the filament must travel, making them more reliable, but the direct extruder is bulky and heavy which can cause more vibrations making the hot end wobble, which can decrease the accuracy. A direct extruder is also tends more expensive [38].

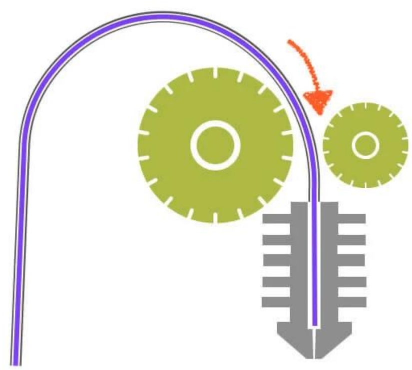

Figure 1:Diagram of a direct drive extruder [38]

Bowden Extruder

Bowden extruders have their cold end located away from the hot end and. However, both are connected through a flexible Teflon tube long enough to connect to both components. This makes the setup for the Bowden extruder slightly more difficult. Having the extruder separate from the hot-end (Figure 2) allows for the hot end to be the only thing that needs to move around during printing, which is better for smaller printers and gantries that cannot handle much stress. One of the weaknesses of a Bowden extruder system is that it is less reliable due to the filament having to travel a distance between the extruder and hot end [38].

Since the goal of this project is a printer capable of making small parts, and the hot end is smaller and lighter, we want to use a Bowden system since without the feeder attached. We can attach the feeder elsewhere on the frame out of the way.

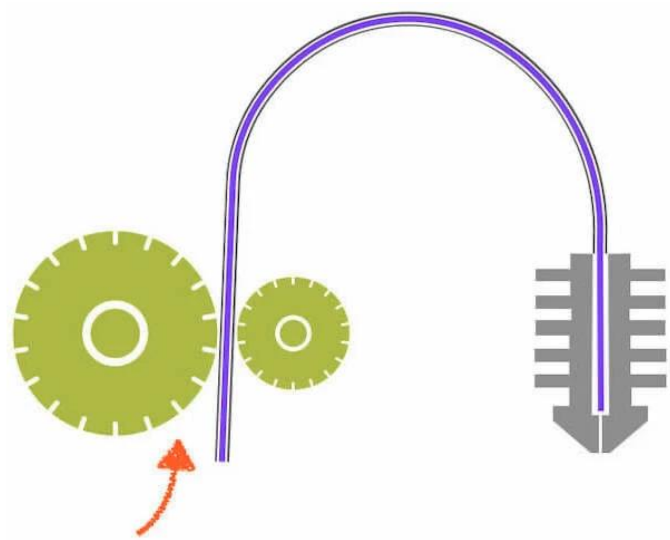

Figure 2: Diagram of a Bowden extruder [38]

Stepper Motor and Filament Feed

The stepper motor feeds the filament to the hot end through a gear system that is hooked up to it. As the motor turns the gears turn as well in the direction, they need to rotate in order to feed the material or eject the material in case of a filament change [38].

Heatsink

The purpose of the heatsink is to absorb heat from the object it's attached to without the need of a fan or a water-cooling device [42]. Heatsinks are located on the printhead above the nozzle and hot end to effectively cool the area where the filament flows before it reaches the heater block. Without a heatsink the components could overheat, causing deformations in the part being printed and damaging the filament being used [38].

Hot-End and Nozzle

Even though the hot-end and the nozzle are two separate components, they are both connected and work for the same purpose. The hot-end is the final step before the filament reaches the nozzle. After the filament is hot enough to print, the hot-end and the nozzle end up having a very similar function, which is to melt the filament and print. The nozzle's material can be replaced depending on the material the user is trying to use. The most common materials are brass, nickel-plated brass, nickel-plated copper, hardened steel, stainless steel, and brass or copper with ruby tip [21].

2.2.5 Controller Board – CNC Shield

Computer numerical control (CNC) is programmed code representing instructions for precise movements carried out by machines. The Arduino CNC shields provide an Arduino microcontroller with the power necessary to drive stepper motors and run all the other functions that contribute to a machine’s operation [39]. Depending on the shield, this could include end stops, spindle speed control, and probing. The CNC shield is responsible driving the motors and other electric components and controlling them to complete the necessary task.

2.2.6 Motors and Drivers

To run the different axes mechanisms, statics motors are interconnected with the multiple moving pieces of the printer to drive them. This is possible through component combinations such as leadscrews or pulleys and a belt. These are standardized parts that work together allowing the X-Y and Z axes movements. A motor driver controls the speed, torque, direction, and resulting horsepower of a motor [47]. The motor drivers are connected to the CNC shield, which as mentioned before controls when and how the other components are working.

Leadscrew

A leadscrew is a threaded metal bar and a threaded led nut that remain connected in order serve as a linear actuator. This component, also known as “power screw”, transforms circular motion (screw rotation) into linear motion (threaded nut path). In these systems, there is not big amounts of energy transmission due to friction between components. Leadscrews could be utilized for vertical and horizontal movements and could be activated manually or by motors. The screw is usually manufactured out of metal, but depending on the application, the nut could be made of different materials. Small to medium applications implement plastic ones while heavy duty applications will require metal ones [28].

To ensure accuracy and decrease vibration and slop of this component, an anti-backlash nut is needed. This is a pre-loaded nut that while being in contact with the leadscrew nut, minimizes any looseness between the faces of the screw [28].

The leadscrew is a cost-effective option for axes movement. They are compact, easy to incorporate to any design and remain fixed in place enhancing smooth operation [28].

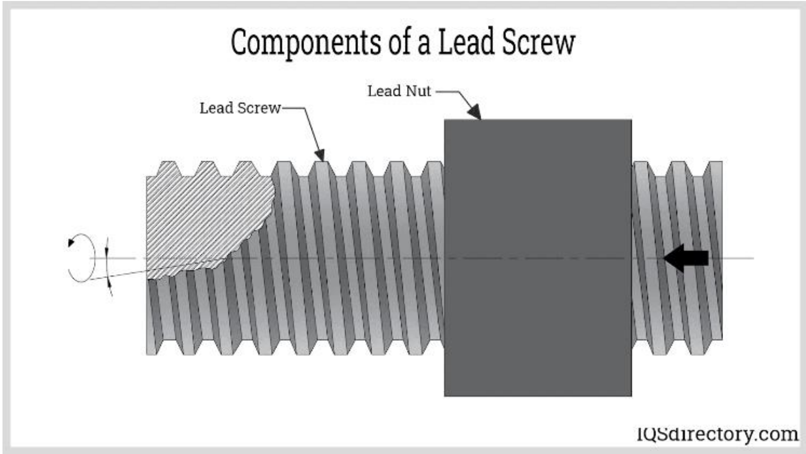

Figure 3: Diagram of a leadscrew [32]

Belt and Pulley

A belt and pully system is built with two or more pulleys turning around axles connected through a timing belt. This basic mechanism allows mechanical power transmissions over determined distances. There are multiple pulley/belt configurations for different applications depending on the amount of torque needed [17].

Timing belts are regular flat belts on one side and toothed on the other. This feature enables precise control over the position of the entire system. In this case, power is transmitted though the belt's teeth instead of relying solely on the friction between the belt and pulley [17].

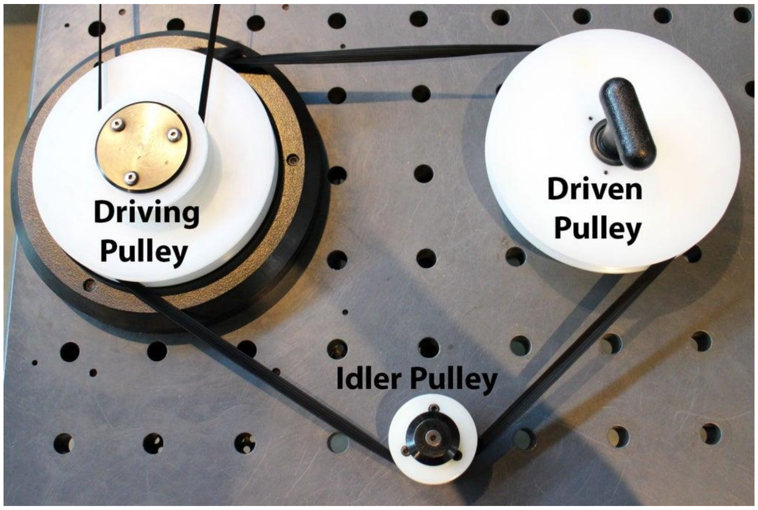

Figure 4: Driving, driven, and idler pulleys [17]

There are different types of pulleys that could be used. Some of the most common ones are the driver pulley, the driven pulley, and the idler pulley (Figure 4). The first is the “input” pulley; the one whose shaft is being driven either manually, with a motor, a crank, or similar driver. The driver pulley controls the motion of the system. The second type is the “output” pulley; it rotates as a result of the belt’s displacement. Finally, the third type is the idler pulley. This one does not transmit any power from its shaft itself; it rotates freely, and it’s often connected to other actuator in the system [17].

Belt and pulley systems could be used in a wide range of applications from small to heavy duty ones. In the 3D printing field, it is a very common mechanism for the X-Y movement. The advantages of utilizing them is mostly the low cost and ease of acquisition.

Figure 5: A pulley and timing belt mechanism [17]

2.2.7 Limit Switches

Limit switches are electromechanical sensors that detect the present or absence of a body in a determined location. They activate when the actuator comes in contact with an object and generates an electric signal. There are various models of limit switches. However, the size and geometry depend on the available space in the assembly and the mechanical set up [16].
In 3D printing, limit switches allow the main components, such as the bed and the extruder, to set the coordinates where they should be operating and moving towards.

Figure 6: Small limit switch [16]

2.3 Software and Hardware

Once all the mechanical design is completed and ready, it is time to run the printer. In order to make a 3D printer function, three main components need to work together. There must be hardware, firmware, and software.

The hardware is the physical prototype along with the Arduino board, motors, limit switches, drivers, cables, and push buttons. These will send commands activated by the physical components into electrical signals.

The firmware is software that's embedded in a specific piece of the hardware. The firmware is incorporated during the manufacturing process. It is used to run user programs on the device. It is the software portion that allows the hardware to function. Hardware manufacturers utilize embedded firmware to control the functions of several hardware devices and systems [22, 55].

The software is the program that acts as a set of instructions that tells the hardware how to operate. The software is the computerized data that is made for the physical hardware to work with specific applications. It is basically known to be the contrasting element of a hardware system [50].

2.3.1 Arduino

Arduino is an open-source electronics platform that offers user-friendly hardware and software. Arduino boards can read inputs, such as a wide range of sensors and buttons, and turn it into an output, such as operating motors, turning on LED lights, etc.

The board’s task execution depends on the set of instructions to the microcontroller on the board. In order to deliver these instructions, the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing are necessary.

There are multiple microcontroller brands in the market. However, Arduino leads the field since has the following advantages:

a. Low cost compared to other brands (50>)
b. Compatible with multiple operation systems
c. Simple and easy-to-used programming environment
d. Open source tool and extensible software

In Section 4.1.2 we will explain how we utilized Arduino hardware and software to run our 3D printer components [54].

2.3.2 Marlin Firmware

Marlin is an open-source firmware designed for RepRap based FDM 3Dprinters utilizing the previously mentioned, Arduino platform. Marlin Firmware runs on the 3D printer's main board, managing all the real-time machine tasks. It operates the stepper motors, heaters, limit switches, buttons, and any other components that come into play in the process of 3D printing [56]

Marlin uses derivative of G-Code as control language. G-Code commands tell a machine to complete tasks with its different components. In order to print a part using Marlin, it must be converted to G-Code using a “slicer” program beforehand. Given that all 3D printers operate differently, each file needs to be sliced with a compatible slicer. G-Codes themselves are not downloadable from the internet [56].

As Marlin receives movement commands it adds them to a movement queue to be executed in the order received. It processes all different components at a time so the print could be completed as smoothly as possible [56].

Marlin only operates with G-Code, however, most slicers only slice STL files.
As long you can export a solid model, a “slicer” such as Ultimaker Cura or Slic3r can slice it into G-Code, and Marlin firmware will print the desired part [56].

When it comes to printing, Marlin could be operated entirely from a host or on its own from an SD card. An independent SD print could still be initiated from a host; therefore your computer can be untied from the printer. Host software is available for several platforms, such as Arduino and Raspberry Pi. Any board or device with a USB port and serial terminal could act as a host. However, a better printing experience is guaranteed using host software specifically designed for 3D printers. For our project, we chose to utilize Pronterface, an opensource host that will be discussed in the next subsection [56].

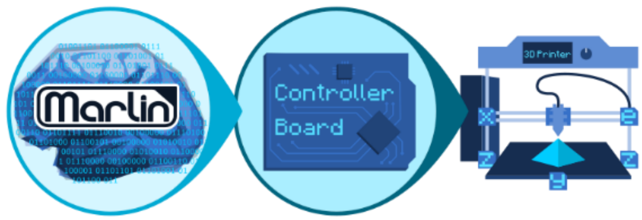

Figure 7: Infographic on Marlin's control language used for 3D Printing [56].

2.3.3 Pronterface

We plan to use Pronterface to control and run the Palm Print printer. Pronterface is a graphical interface that interacts with the Marlin operations. It is part of a set of software from a group of G-Code tools named "PrintRun".

Pronterface translates the Marlin code previously indicated and runs the G-Code you feed it to control the printer [57]. It is also possible to manually control the X, Y, Z axes and extruder tasks. Each 3D printer is coded individually in Marlin based on its unique parameters. Marlin Firmware has a generic configuration code. It is necessary to study it and change the lines and commands that are unique to your machine. These parameters depend on the Arduino board set up and wiring, discussed in Section 4.1.2.

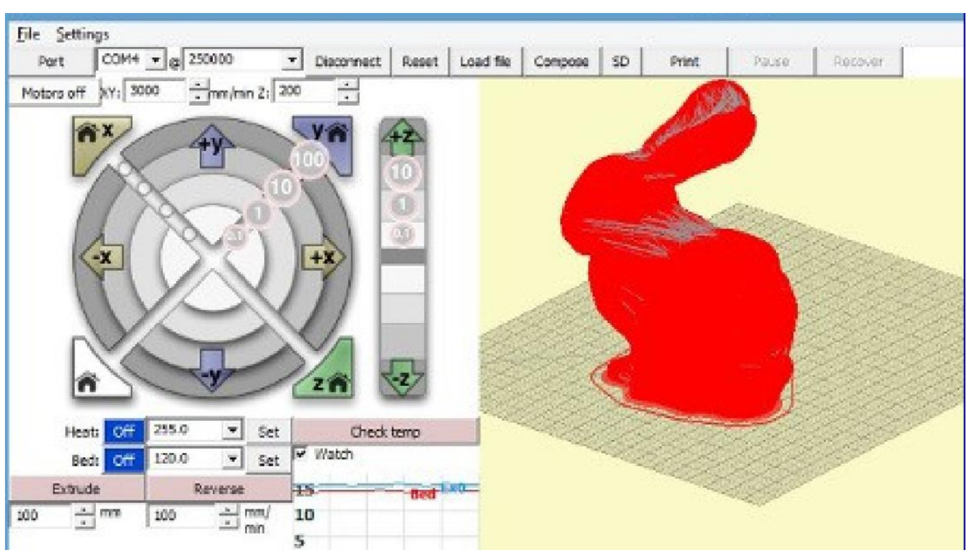

Figure 8: Pronterface GUI [48]

2.4 Different Types of FDM 3D Printers

When making a FDM printer, there are a few different options of the for deciding what kind of kinematics to pick for the printer to design. The options include a rectilinear, polar, delta, or SCARA printer, which all have the same function, but use a different kind of coordinate system for providing the motor with movement direction [44].

2.4.1 Cartesian Rectilinear FDM Printers

Rectilinear printers are printers thar read a given movement command in one liner direction at a time. This means that when making the CAM for the printer and slicing the G-Code, the code will produce movement instruction in cartesian coordinates, and the motors will follow the given command by moving the hot-end in one given direction at a time. Within the rectilinear cartesian printer category, there are different movement systems that can be designed such as the H-Bot and Inverted, CoreXY, and individual axis movement [44].

H-Bot and Inverted H-Bot

The H-Bot, shown in Figure 9, is a kinematic mechanism powered by two motors and a single belt, along with pullies, and with these parts, the design of the mechanism will allow for a 2-Degree of Freedom (2DOF) mechanism. The H-Bot design is given the name because the belt will form the letter “H” when looked at from above. This design is known for optimizing the print area, the ability of handle printing at high speeds, and producing models with high accuracy. However, low-tensioned belts can lead to inaccurate movements while overly tensioned belts will increase wear and tear greatly. The Inverted H-Bot design, Figure 10, has the same features as the H-Bot but there will be one vertical bar as opposed to 2, decreasing the part count [44].

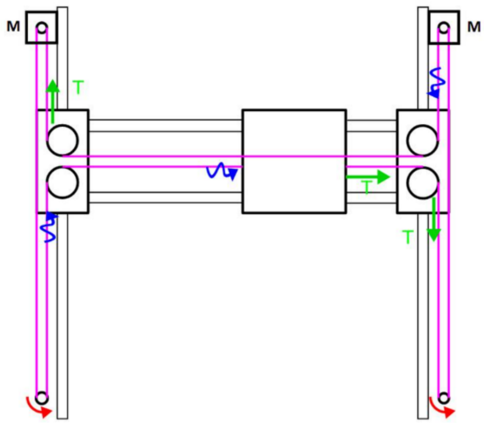

Figure 9: Diagram of an H-Bot mechanism [1]

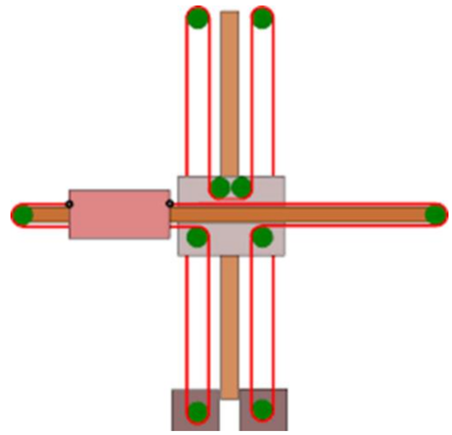
Figure 10: Diagram of an Inverted H-Bot mechanism [24]

CoreXY

The Core XY (Figure 11) is a motion mechanism composed of two to three motors, and more than one belt and pulleys. The belts are arranged so that the motion of one motor causes the tool to move at a 45-degree angle. That means both motors move in a straight line. This is the mechanism mentioned in the 2020-2021, used as the Z-X axis. The movements of the CoreXY are not only very precise and compact but also repeatable and linear. Therefore, CoreXY systems are becoming more and more popular [44].

The CoreXY design can handle printing at high speeds, and the connection of the motors to the frame helps in reducing the vibration significantly, which also contributes to high-quality printing. However, there are some downsides to the CoreXY. The belt system is not necessarily reliable if it is not set up correctly [25]. Too much or too little tension can cause inaccuracy in the prints or could cause some wear on other components. Also, if the frame of the printer is not perfectly square when using a CoreXY system, the print may also eventually lack accuracy and make low quality prints, and this design has a higher part count [44].

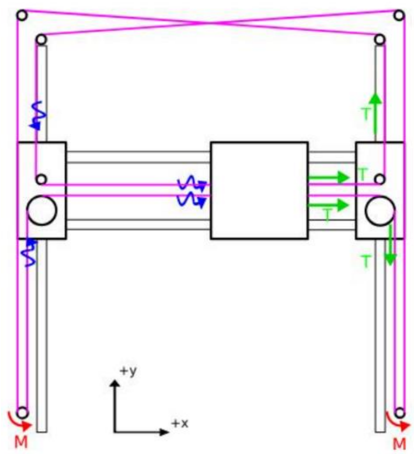

Figure 11: Diagram of a CoreXY mechanism [1]

2.4.2 Delta FDM Printers

Delta 3D printers use cartesian coordinates as well, but they are made up of three arms attached to vertical rails. The hot-end then attaches to end of each of the arms, and the arms will move in a coordinated manner to control the print height from the print bed. These printers are not controlled by a fixed axis which makes it different from other cartesian printers. The strengths of delta printers include the fast print speed, high print quality, and ability to print large prints. The printers however are difficult to maintain, have a small build area, and tend not to be compatible with direct drive extruders [44].

Figure 12: Example of a Delta 3D Printer [1]

2.4.3 Polar FDM Printers

Polar 3D printers are much different than most other 3D printers when it comes to coordinated movement. Polar printers will use a polar coordinate system which means the positioning of the hot-end is determined by angles and distance, rather than by X, Y, and Z coordinates. This is represented by the plate moving in a circular motion while the extruder moves in the Z direction when reading the G-Code. One of the benefits to this style of printer is that it will only need two motors as opposed to three for diving the hot-end to the desired location [44].

Figure 13: Example of a Polar 3D Printer [46]

2.4.4 SCARA FDM Printers

A Selective Compliance Assembly Robot Arm (SCARA) 3D printer is a printer that operates using cartesian coordinates, however the printer contains a unique mechanical design. The SCARA printer consists of a hot-end connected to two robotic arms and being driven by two linkages and two motors. Another motor will be responsible for driving the Z direction movement, either by controlling the height of the print bed or the height of the robot. Typically, the build plat is not attached to the robot, as the robot will be mounted to a structure, and they have proven to be imprecise, with little support on how to use the printers [44].

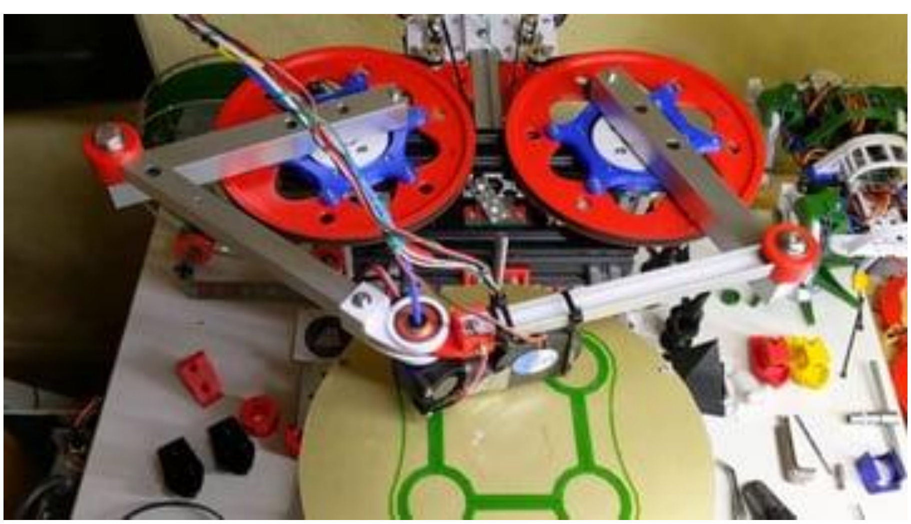

Figure 14: Example of a SCARA 3D Printer [44]

2.5 Existing/Similar 3D Printers

There are many available printers in the market that are starting to meet a fair budget for customers. Some of them reach similar standards to what the team is looking for on the Palm Print, while others are consumer favorites, or demonstrate portability.

The PocketMaker is a small and budget friendly 3D printer. The printer costs less than $100 and has a print bed volume of roughly 3.15" x 3.15" x 3.15". This printer can easily be transported and carried to other locations which make it a consumer favorite for a small and inexpensive printer [29].

Figure 15: PocketMaker 3D Printer [19]

The Creality Ender 3 (Figure 16) is a very competitive and reliable 3D printer on the market right now. It sells for $250 or less in multiple electronic stores and contains a reputable design and selection of parts. The Ender 3 uses a CoreXY design for the hot-end movement mechanism, and uses common parts, which means that if any maintenance needs to be done on the printer, parts will not be difficult to find. The Ender 3 uses a glass print bed but allows for the option of a magnetic Spring Steel PEI print bed sheet [52].

Figure 16: Creality Ender 3 [20]

The Original Prusa MINI+ (Figure 17) is a user favorite when it comes to the size and portability, and the quality offered by a small printer, all while under $400. The Prusa MINI+ uses a simple Cartesian Rectilinear design and measures at roughly 13” x 13” x 15” while allowing for a print volume of roughly 7.1” x 7.1” x 7.1” [27].

Figure 17: Original Prusa MINI+ 3D Printer [27]

2.6 Palm Print (2019-2020) Design Review

The first Palm Print prototype was manufactured in the years 2019-2020. The team created a model that successfully met some of the printer's requirements like size, portability and budget as well as meet a lot of setbacks.

The X-Y mechanism of the printer was driven by two 5V stepper motors, two belts, and four pulleys. It is composed of the print bed and a bottom slider, both riding on parallel rods. In both sliders the previous group implemented a V-shape groove in one side and a slot shape in the other, this allows the parts to slide on the rods with minimal friction and stay on track at the same time. On the bottom of the rods applying a small amount of pressure are 3D printed pre-loads, which help keep the parts on track without impeding movement.

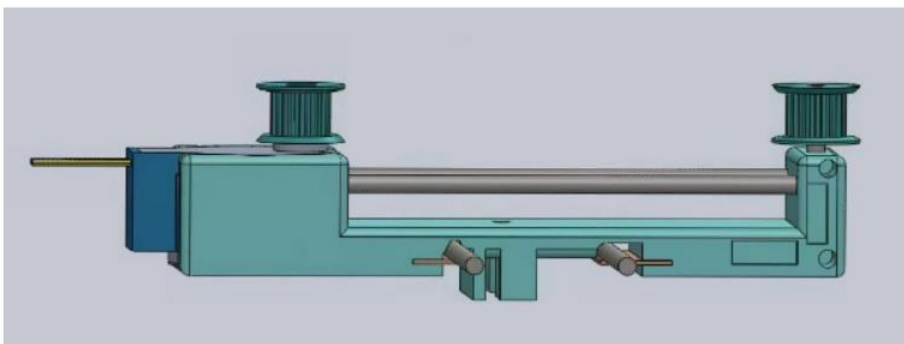

Figure 18: Rod and slot used 2019-2020 Palm Print design

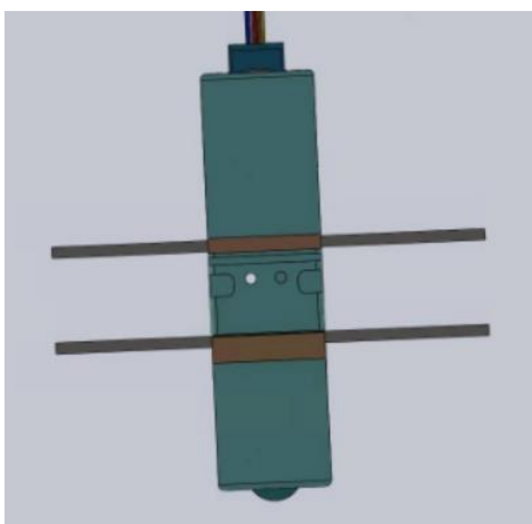

Figure 19: Pre-loads used in the 2019-2020 design

The idea for the X-Y mechanism overall was good, however when put into practice, it didn’t work as expected. The pulleys weren't correctly attached to the motor and fell easily. The whole system was completely unstable and had a lot of “wiggle” or looseness, and the motors where never able to move the bed smoothly. Due to these reasons this X-Y mechanism had to be moved away from.

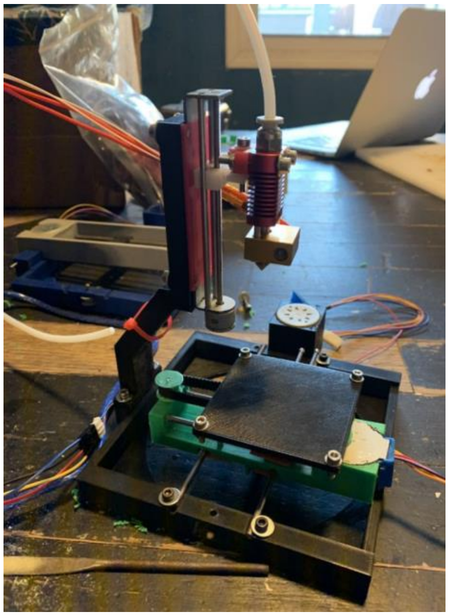

Figure 20: Assembled 2019-2020 Palm Print prototype

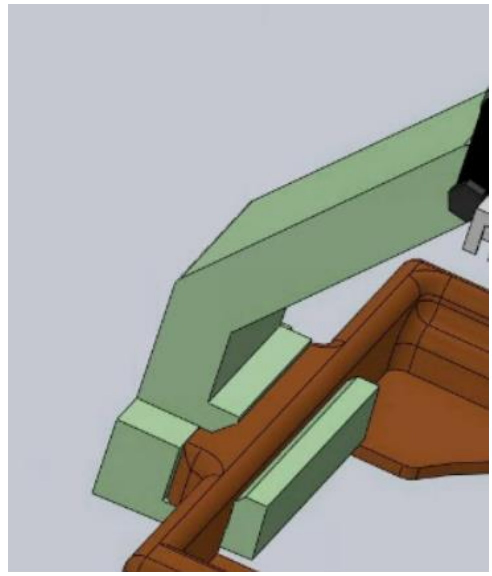

Figure 21: Attachment mechanism used in the 2019-2020 Palm Print design

The Z mechanism was a simple but very clever system. The team bought a stepper motor that came with an integrated lead screw which was able to successfully lift the extruder up and down. The main takeaway from the model was the way they were able to make the Z axis detachable from the base with the purpose of portability. It works in a sort of snap fit mechanism in and helps on a smooth and easy disassembly (Figure 21).

2.7 Palm Print (2020-2021) Design Review

The second team that took over the project took a very different approach to the Palm Print: 3D Printer. They prioritized portability over the other aspects of Palm Print, designing a printer that fold open and closed while maintaining a small size factor. This team went with a CoreXY movement mechanism and were able to accomplish a complete assembly of their 3D printer. However, the printer was never able to be properly tested for printing, so it remains to be known if it’s functional.

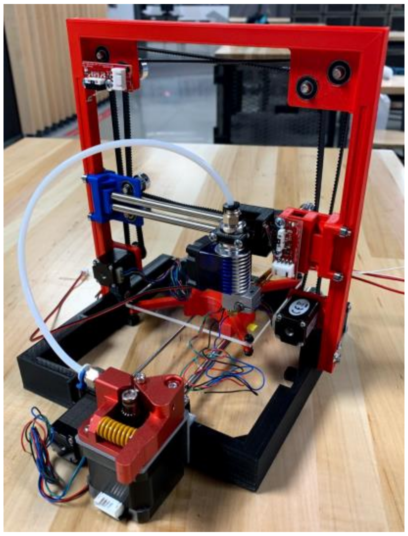

Figure 22: Assembled 2020-2021 Palm Print prototype (open)

The main take away from this model is the collapsing Z mechanism they developed, which puts the components away in a neat way and gets the printer ready to be taken anywhere. However, when put back together it doesn’t secure correctly, making it unstable. In addition, the print bed was unstable and wiggled a lot. With these aspects in mind the model overall defeats the purpose of the Palm Print because of the big size. If this printer can be decreased in size and in part count the model would be a good option, without those changes it is a model that needs to be moved away from.

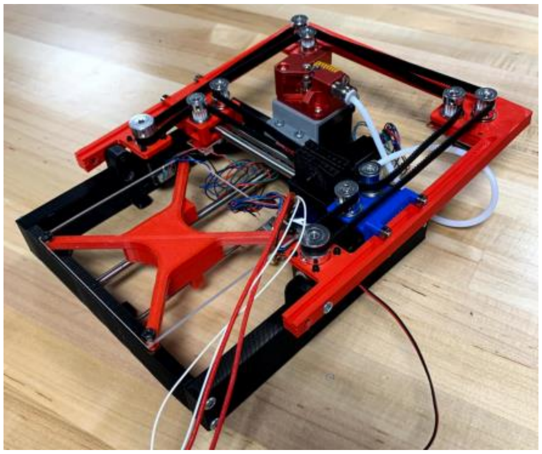

Figure 23: Assembled 2020-2021 Palm Print prototype (closed)

3. Methodology

Designing the new iteration of the Pam Print: Portable 3D Printer we wanted to find a way to incorporate some of the designs used by the previous project teams, while still improving on the product. As a group, we made mind maps for brainstorming ideas, before opening up Fusion360 for CAD, 3D printing and assembling the parts.

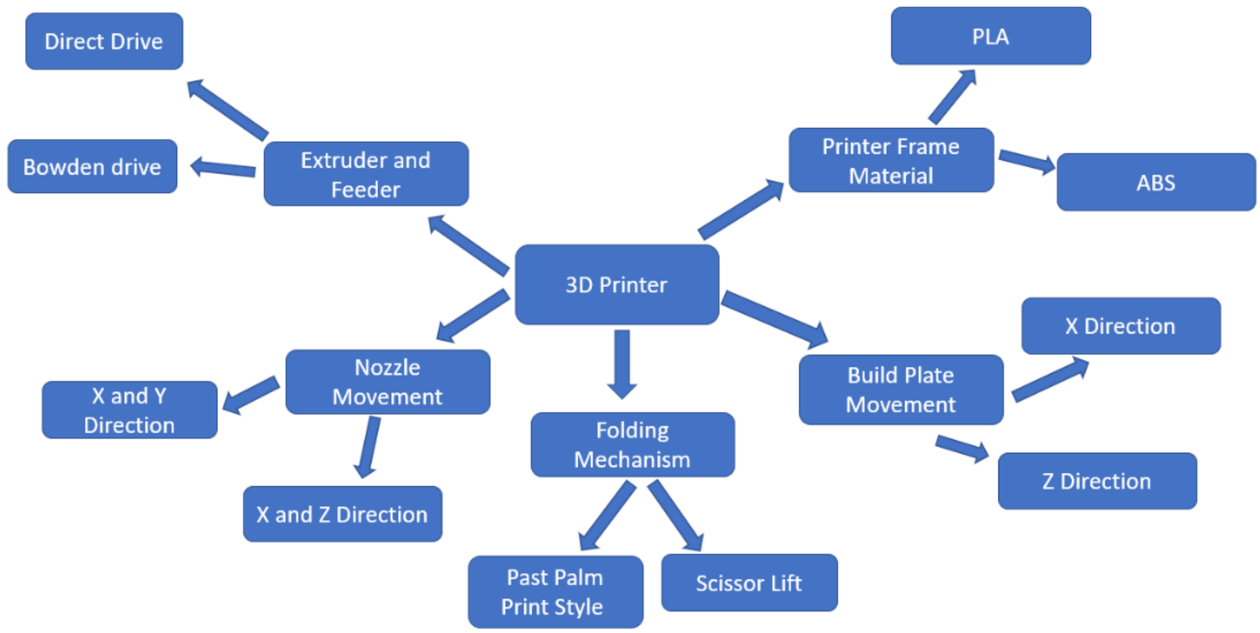

Figure 24:Mind map of the different components that are needed in a 3D printer and what part they would connect to

3.1 Ideation and Design Reviews

To develop our final prototype, we needed to explore different moving mechanisms. These allowed us to replicate their functional features and avoid the ones decreasing practicality, life cycle and design feasibility. Table 3 below represents a material comparison chat that we made to help determine the direction the take the design. In this section, we discuss the brainstorming process that led the team to study the Scissor Mechanism, H-bot, Inverted H-bot and Core XY and their existing features.

Table 3:Mechanism comparison chart for the different 3d print movement mechanisms

Mechanism Comparison Chart					
Mechanism	**Ability to shrink**	**Stability**	**Movement**	**Accuracy**	**Foldability**
Core XY	High, but printing area decreases	High	Nozzle moves in X and Y directions/ bed moves in the Z	High	High
H-bot	High	High	Bed moves up and down/ Nozzle in X and Y	High	High
Delta	Low	High	Stationary bed, 3 moving arms	High	Low
Polar	High	High	Polar coordinates	Low compared to delta and cartesian	Medium
SCARA	Low	High	Two robotic arms + z-axis bed	Low compared to delta and cartesian	Low

We then created another mind map that included different kinds of ideas for movement mechanisms, as well as some improvements that could be made to the last iterations of the Palm Print design (Figure 45).

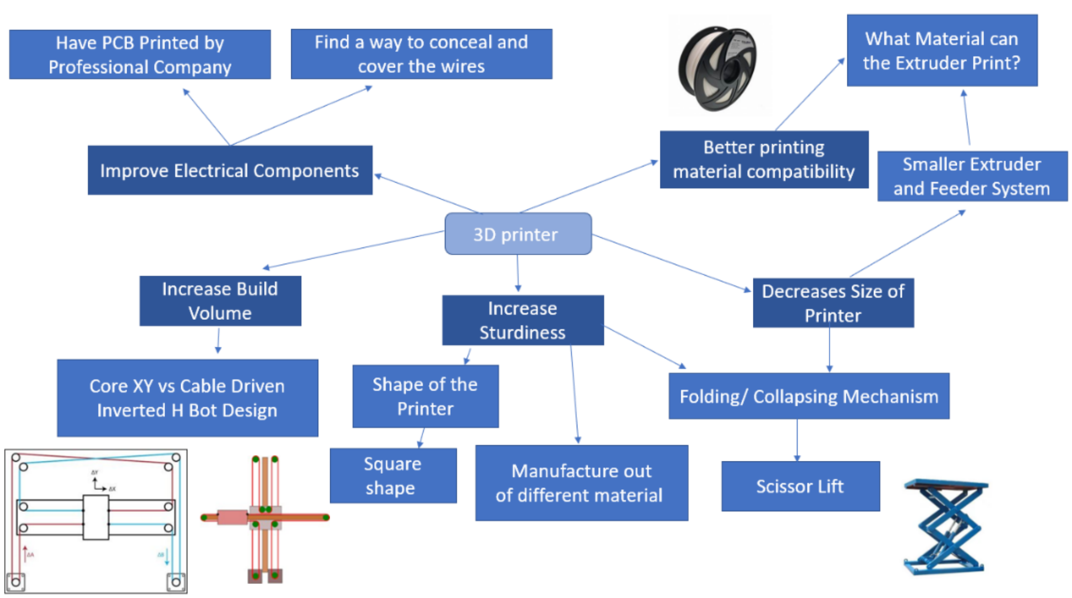

Figure 25:Mind map of the models to make for feasibility testing

3.1.1 Scissor Lift

While conducting research for the background section, we came across a personal project where the user designed a 3D printer using rails and linkages in the configuration of a scissor lift so it could fold into a suit case and be easily transported [24].

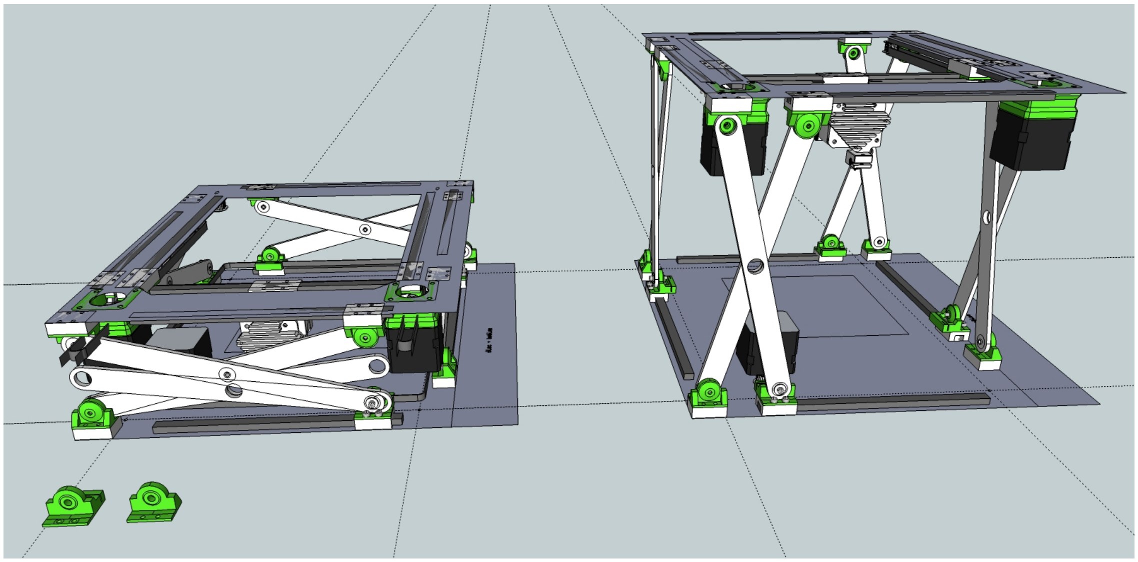

Figure 26:Example design of a scissor lift portable 3D printer frame

From the above design a CAD model of a frame was created to represent a scissor lift mechanism, with rails to represent an Inverted H-Bot on the top frame of the, and an opening that can be seen on the left side of the figure to represent where the Bowden extruder would be located.

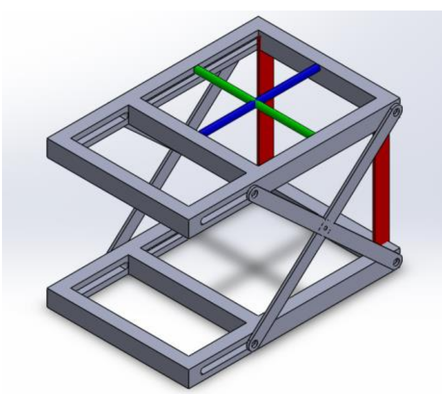

Figure 27: Isometric view of the scissor lift CAD brainstorm

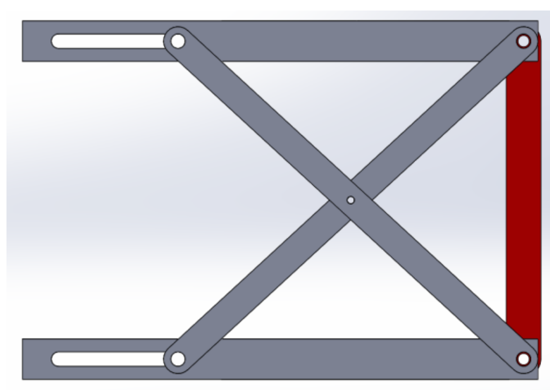

Figure 28: Right view of the scissor lift CAD brainstorm (open)

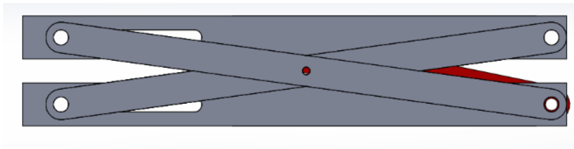

Figure 29:Right view of the scissor lift CAD brainstorm (closed)

The next step was to add the motors to the design, which changed the base layout of the design, and removed the storage space for the extruder. The design created includes the use of four NEMA 14 motors that would connect by a collared shaft to a lead screw. The lead screw would have a nut attached to the linkage and the other linkage would be sliding on a rod on the top section of the mechanism. When all four motors run simultaneously, it would cause the scissor mechanism enclosure to open and close which would be used for storage, while also acting as the Z direction movement of the printer.

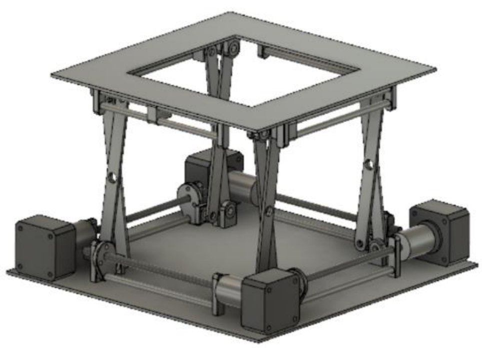

Figure 30:CAD model of updated scissor lift mechanism with motors (open)

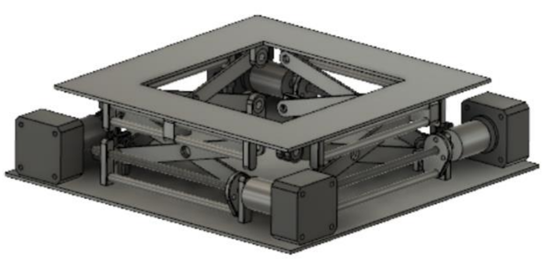

Figure 31: CAD model of updated scissor lift mechanism with motors (closed)

When the model was ready to be printed, the size of the bottom base was decreased so it could fit on the printer we have access to in the Makerspace, so the motors would not be present on the actual printed model. This model would have the capabilities of housing a print bed with a print volume of 4” x 4” x 4”, and with a base area of 8” x 8”. The model proved to be stable and rigid while in both the open and closed linkage positioning and would provide for an adequate build plate volume. The attachment to the linkages were not as successful, it was not stable, and the linkage was coming out of place easily. A shoulder screw could be put through the linkage into the slider to improve the connection, which is important because it would be maintaining the linkages at the same angle while model is moving up and down.

The slider was attached by two holes on the attachment piece, which proved to be an issue due to friction not allowing for the attachment to slide smoothly on the rails. Through looking at the past designs of the project, we were able to find, that we could decrease the friction between the attachment and the slider by using a “V” shape and a slot design instead of two holes for the connection of the attachment to the slider. Another problem with this design is the use of 4 motors, which would have a significant increase in the total price of the product and increase the part count and weight.

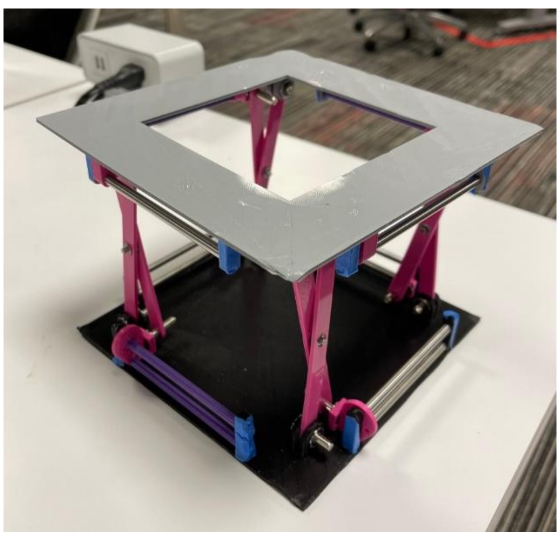

Figure 32: Assembled feasibility prototype of scissor lift mechanism (open)

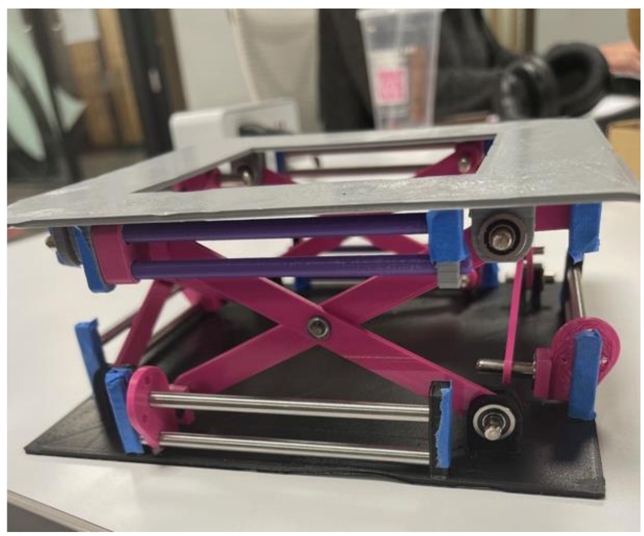

Figure 33: Assembled feasibility prototype of scissor lift mechanism (open)

3.1.2 H-Bot

The purpose for this H-Bot model was to be placed either on top of the Scissor Folding Mechanism mentioned previously, or as the base of the mechanism as the print bed movement. The mechanism had some good features including size and cost. Since this was planned to be a component mounted on the 3D printer it had to be kept to a minimum in respect to the features mentioned above.

The fist iteration of the H-Bot was design to run on a rail system, as seen in Figure 34, which had to be changed immediately. When assembled without a belt, every sliding component was unstable, which led the team to realize that controlling the movement of the system with a lead screw could be a more feasible route for us.

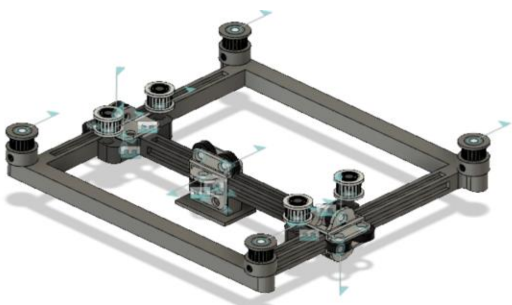

Figure 34: Isometric view of the first iteration of the H-Bot model

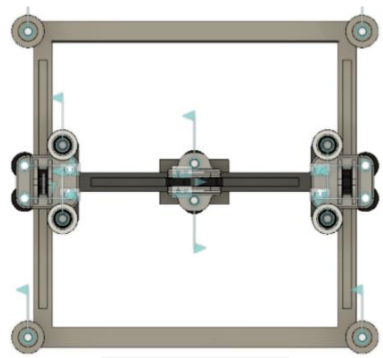

Figure 35: Top view of the first iteration of the H-Bot model

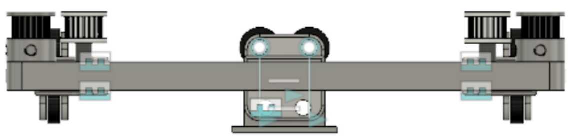

Figure 36: Right view of the first iteration of the H-Bot model

The movement mechanism works with two NEMA 8 motors, nine pulleys, and a single belt; composed by a single slider riding on two parallel rods.

The second iteration of the H-Bot was designed with a slot and a groove with pre-loads under them to help with friction and stability, similar to what the 2019-2020 team did with their X-Y mechanism. The printed prototype would've had to be scaled down to fit the Scissor Folding Mechanism.

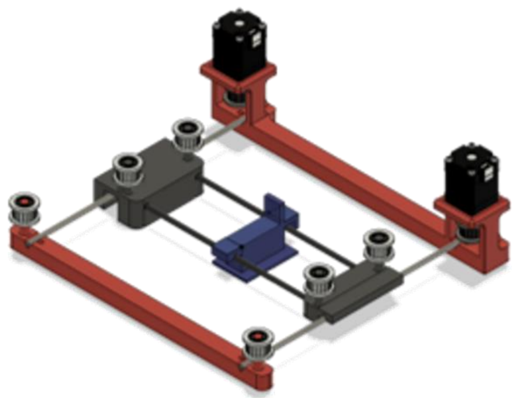

Figure 37: Second Iteration of the H-Bot model with motors

In terms of cost, the prototype was made of mostly 3D printed parts which kept the cost low, plus the previously mentioned components that drive the mechanism. An approximate cost to the mechanism would've been $15, depending on the motors used in the mechanism, since NEMA stepper motors could end up being more expensive than the regular 5V stepper motors.

Some setbacks found with this mechanism were combined with the Scissor Folding Mechanism since some 3D printed parts in the model were not holding or working as we expected. In the H-Bot's case, the 3D printed pins were breaking after so much tension being applied by the belt.

3.3.3 Inverted H-Bot

The purpose for the Inverted H-Bot model was to be placed on the bottom of the Scissor Mechanism for the X-Y movement of the print bed. The mechanism's main feature was its size and the optimization of the printing area due to its orientation. This mechanism included very low-cost and easy to acquire components, which contributed to the prototype's production cost.

The mechanism worked with two NEMA 8 motors, four pulleys, five idlers, eight M3 bearings, and a single belt. These drove the printing bed placed on top of two sliding mechanisms connected through a railing system. This mechanism, as shown in Figure 38, was initially designed without any pre-loads, therefore lacking structural integrity. In fact, these were the challenges that illustrated to the team the importance of including pre-loads in the following iterations.

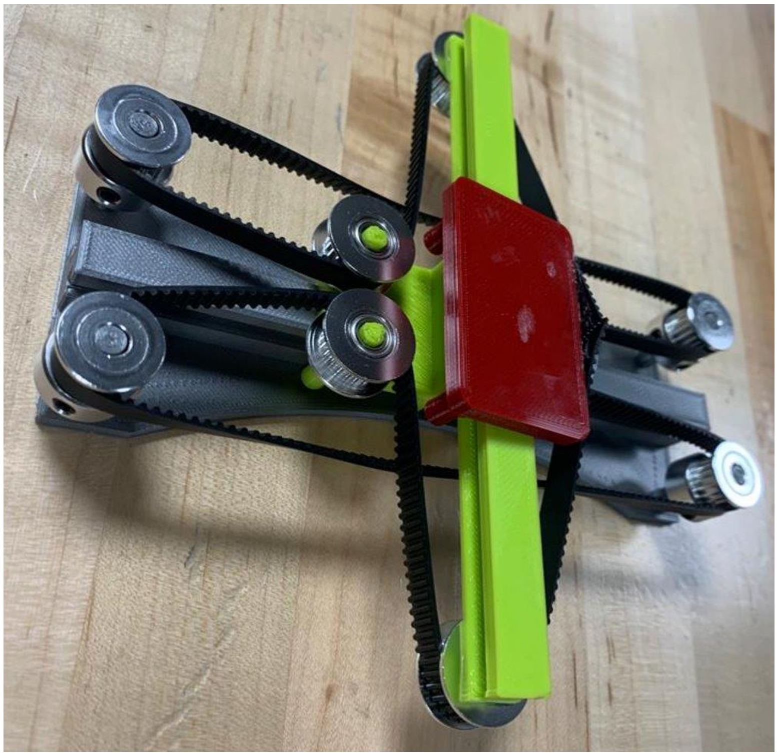

Figure 38: Inverted H-Bot assembly with pully and belt configuration

The design led to improvements on its stability and compactness. The suggestions include adding pre-loads and implementing eccentric screws discussed below. These features would allow for the bed to stay in place and slide smoothly along the rails while maintaining the integrity and stability of all the levels of the assembly.

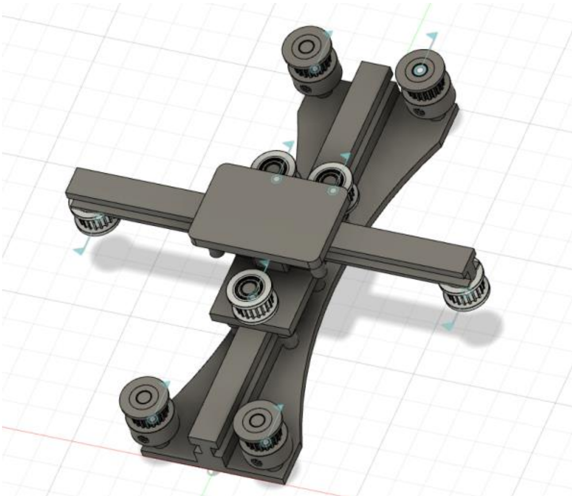

Figure 39: CAD model of the Inverted H-Bot assembly in Fusion360

This printed prototype would've had to be scaled down as well in order to fit within the dimensions of the Scissor Folding Mechanism. The latest version included mounts for the NEMA 8 motors. However, the shafts where the pulleys were mounted, were 3D printed out of PLA and when the belt applied pressure, they collapsed. Therefore, we suggest implementing metal shafts to the assemble in the next iterations (Figure 40.)

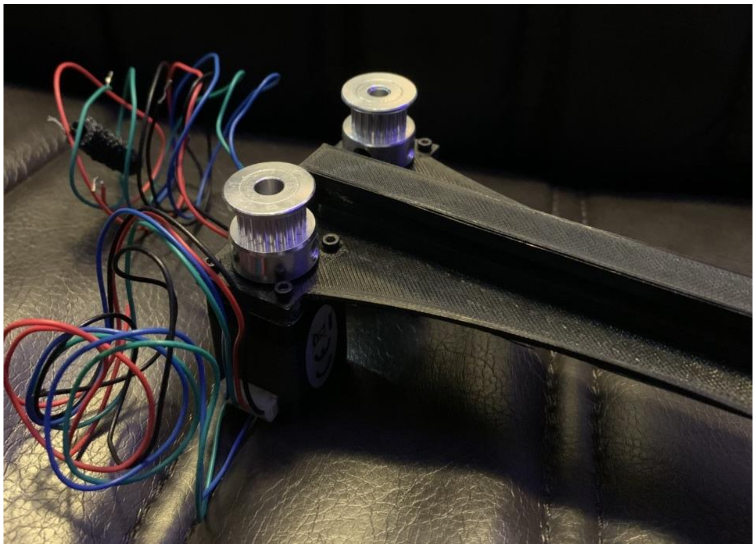

Figure 40: Motor Mounts used in the Inverted H-Bot assembly

The final proposed design includes a slot cut so we could pre-load the bed's bearings into the middle slider railings (Figure 41). This way, the print bed and bearings will lock into place and remain stable.

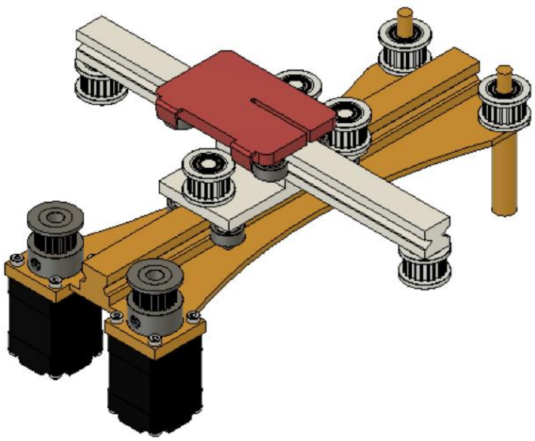

Figure 41: CAD model of the final design of the Inverted H-Bot model

As mentioned before, we suggest the implementation of eccentric screws in order to adjust the sliding components as necessary, as seen in Figures 42. In addition, we suggest including a belt tensioner and a v-sleeve to bearings. The belt tensioner would replace the current belt holder feature and the v-sleeve would allow for a smoother sliding motion on rails (Figure 43).

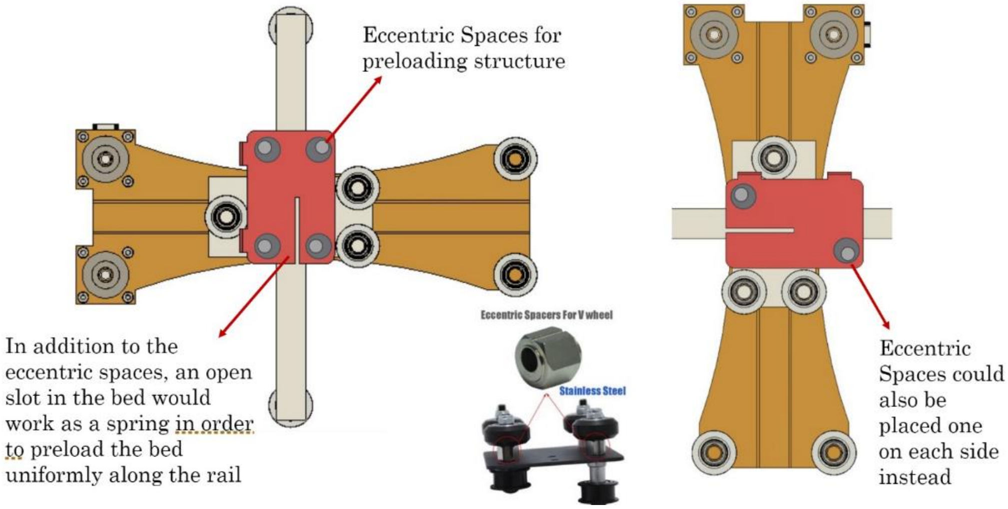

Figure 42: Placement for the eccentric screws on the Inverted H-Bot model

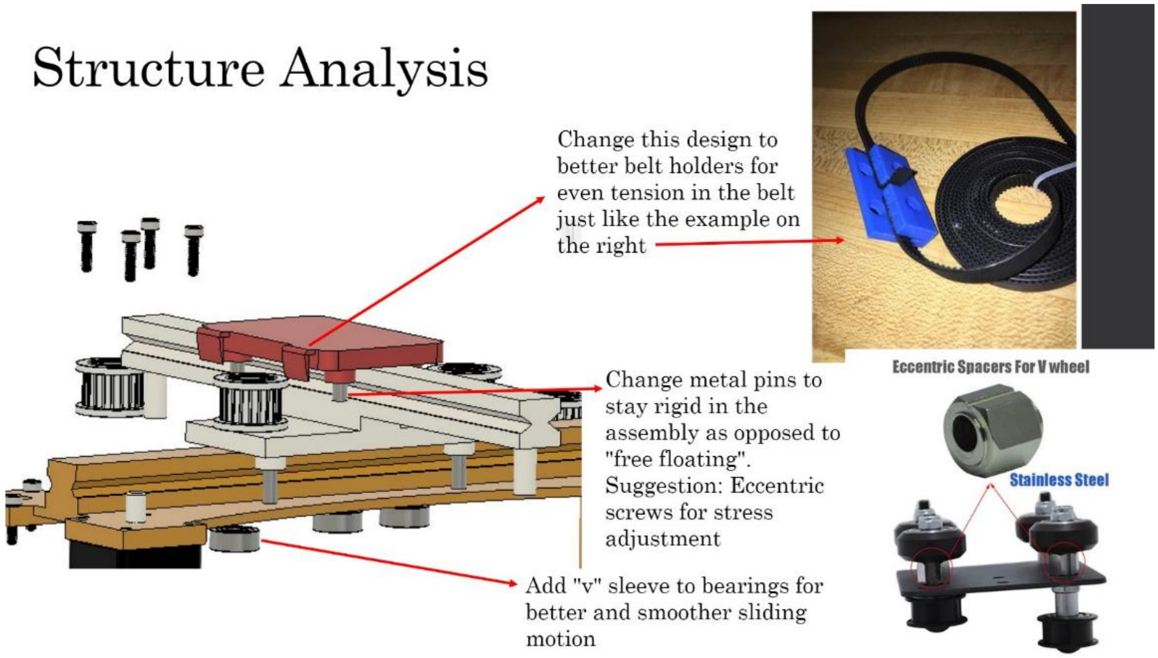

Figure 43: Design suggests for possible iterations of the Inverted H-Bot model

3.3.4 Rectilinear

Looking back at the 2019-2020 Palm Print design, we wanted to consider the simplicity of the traditional rectilinear cartesian printer, because of the how effective the printer could be if we were to improve on the traditional design of a 3D printer.

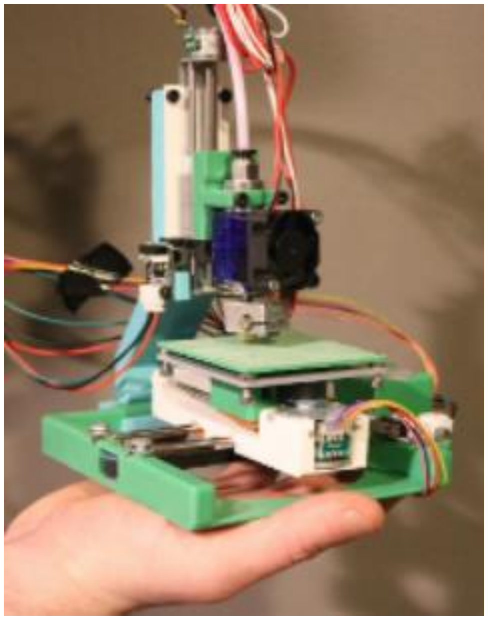

Figure 44: Assembled 2019-2020 Palm Print prototype

We could incorporate and improve on some of the weaknesses of the previous project into our design. Using a simple design like this would allow for a printer with a low part count, and one that could easily be maintained or serviced if needed.

3.2 First Prototype

When creating the first prototype of the printer we wanted to keep the design simple, so we drew from the 2019-2020 design and attempted to decrease the total height of the base that holds the print bed and the slider, while redesigning the print bed and Z direction movement mechanism.

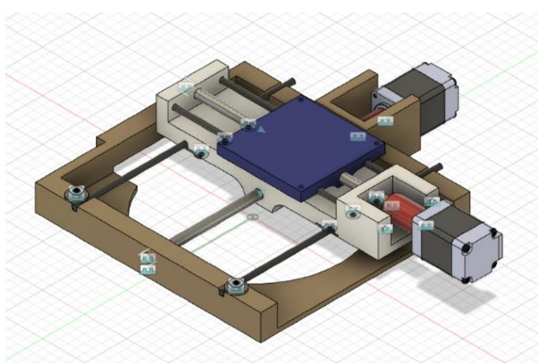

Figure 45: Isometric view of XY mechanism with NEMA 8 motors

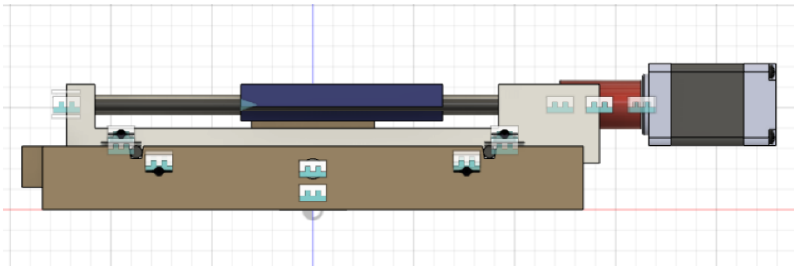

Figure 46: Side view of XY mechanism with NEMA 8 motors

We attempted to use NEMA 8 and NEMA 14 motors on the design instead of the 5V stepper motor that was used originally, but the size and price of the printer would have a significant impact.

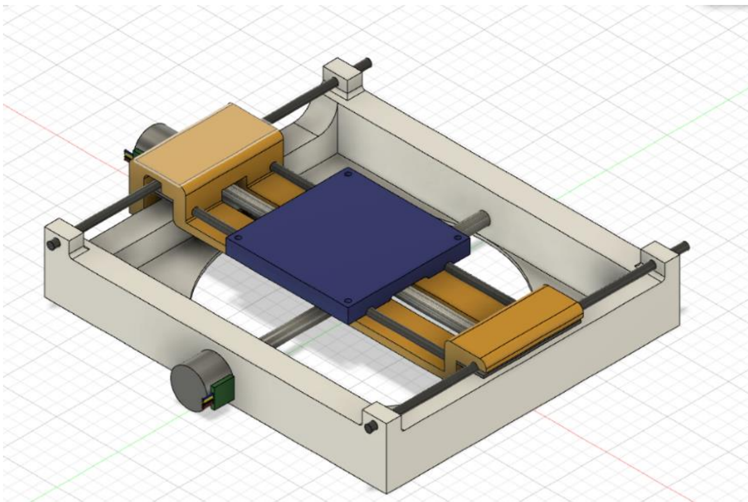

Figure 47: Isometric view of XY mechanism with 5V stepper motors

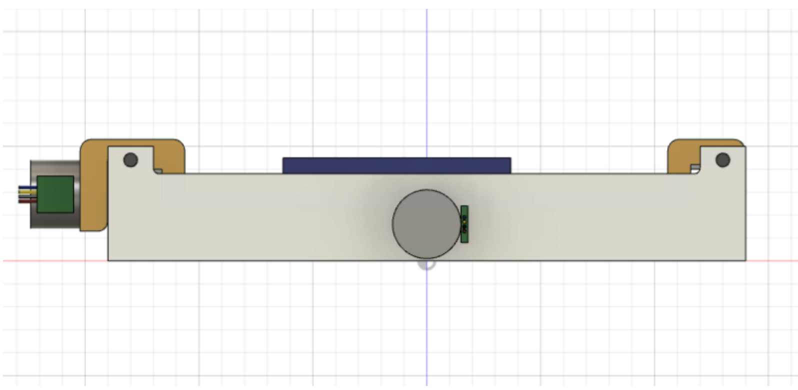

Figure 48: Side view of XY mechanism with 5V stepper motors

Figure 49 shows the team's first approach at what would slowly take form into our final prototype. At this stage it was determined that for the sake of simplicity and staying in budget. The Z axis was not attached, which means that at this point the team's priority was in giving an actual shape to the printer before moving into the portability aspect.

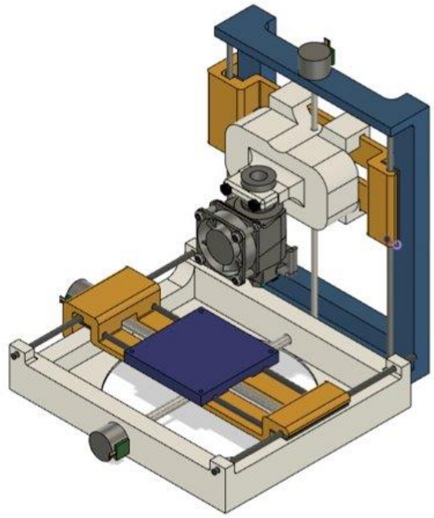

Figure 49: First iteration of the 2021-2022 Palm Print design

3.2.1 Design Review of First Prototype

For this iteration the team periodized the movement and esthetic of the printer without focusing on the portability aspect yet. This helped put all the focus into making sure that every component had a purpose and was well placed.

Both components that move in the X-Y mechanism, similar to previous ideas mentioned, were pre-loaded with 3D printed pre-loads, driven by a stepper motor, and were riding on parallel metal rods. However, to get rid of the belts and pulleys in the past models, lead screws were attached to the bottom sliders. As mentioned previously, some popular 3D printers, like the Prusa, use leadscrews for their movement and it has proven to be successful. Using a lead screw also lowers the part count since the need for the other components was eliminated. and In Figure 49, it can be noticed that the same this was done for the Z axis.

The Z mechanism's (Figure 50) shape was yet to be decided. The assembly for that sliding piece was eventually going to be hard to manufacture. A change needed to be made for the Z axis to be functional. Brainstorming was put into action to determine a shape thar would work for the model and can eventually be turned into a detachable or folding component for portability purposes.

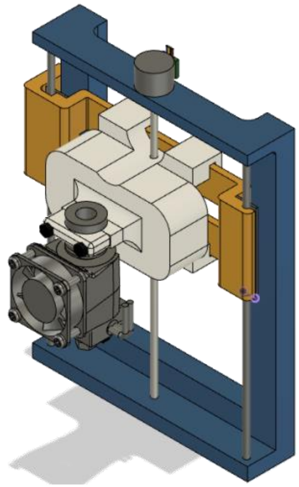

Figure 50: Z-Axis sliding mechanism for the first iteration of the 2021-2022 Palm Print design

While the team was working on the model some setbacks were met. When trying to encounter smaller components, like micro stepper motors or leadscrews with a smaller diameter the price increased by a considerable amount. Smaller NEMA stepper motors were $20 more than regular 5V stepper motors which were $5 each. When looking for 3mm lead screws, some of them were simply not long enough to cover the whole base or were $15 dollars versus a bigger lead screw which would turn out to be approximately $6. These factors obligated the team to take a different route so we could stay in budget.

3.3 Second Prototype

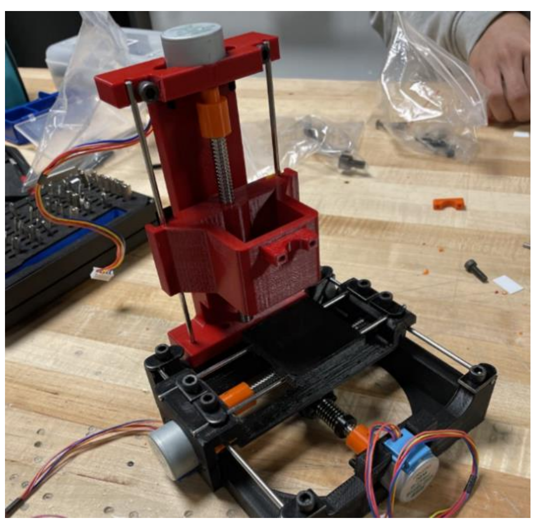

Figure 51: Printed model of the Second Prototype

The model shown in Figure 51 followed up on the previous iteration and added some components. In addition, some changes were made to improve on the reasons mentioned in the previews section. Most importantly this was the first physical prototype the team developed.

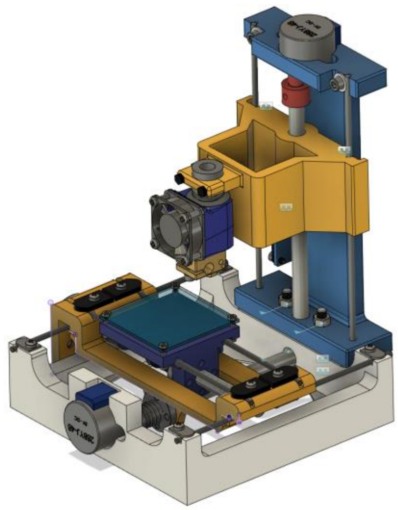

Figure 52: Isometric view of the Second Prototype

3.3.1 Design Review of Second Prototype

With this iteration the negative factors of the previews prototype were fixed. The motors were changed to 5V stepper motors and was changed from a 4mm leadscrew to an 8mm. These changes lower the cost of the printer. The Z axis also had a major change. It was redesigned into an I shape component, that can detach easily by just unscrewing 2 screws in the bottom of the base, as seen in Figure 54. This detaching system fixed our necessity for portability from before since there was no way to attach or detach the Z axis.

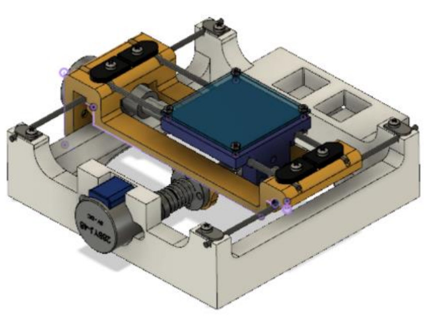

Figure 53: Isometric view of the assembled base mechanism

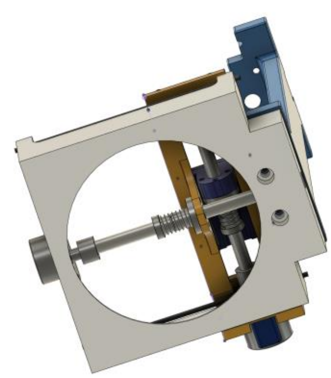

Figure 54: Screw hole locations for base and Z mechanism assembly

In order to attach the lead screw to the motor, a coupler was needed. The cost of a company manufactured coupler is approximately $6, and the size of the couplers were too big for the assembly. That is why the team decided to 3D print couplers which ended up being 8 cents to manufacture our own coupler, shown in Figure 55 below. In order to get the coupler to work correctly, a flat spot had to be made in the end of the lead crew that was going in the coupler. A screw is then inserted into the coupler to lock the lead screw in place.

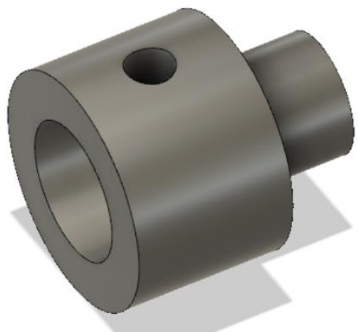

Figure 55: Isometric view of the motor couplers designed

As mentioned before, the Z-axis also went through some substantial changes. In the previous design, the slider component was bulky and complicated to assemble, and the overall frame design had potential to be smaller. Therefore, the square frame was changed to what was later called the "I-shaped" Z-axis pillar. It includes a cut out for the stepper motor on top, a V-groove and a slot to hold the metal cylinders in place and the X-Y attachment on the bottom. The attachment was a new component that contributed to our overall stability goals. It allowed the printer to stay compact and robust after the assembly/disassembly process. The attachment connected with two M4 screws to the bottom of the X-Y mechanism.

The Z-axis slider, the one that holds the extruder, was simplified to a central mechanism guided by the leadscrew. This mechanism that slides on two metal cylinders with the help of Delrin pre-loads integrated into the design for more accurate and smooth motion.

These changes were the biggest the team made throughout the Z-axis model. They were the foundation for the remaining iterations towards the final prototype.

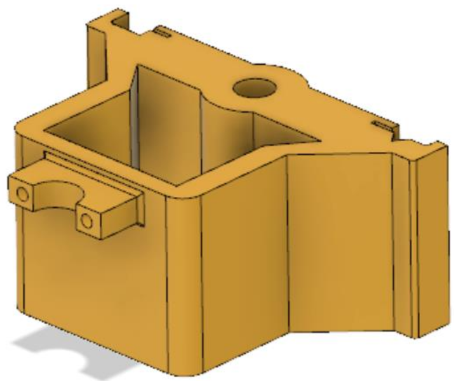

Figure 56: Sliding component in the Z axis that holds the extruder

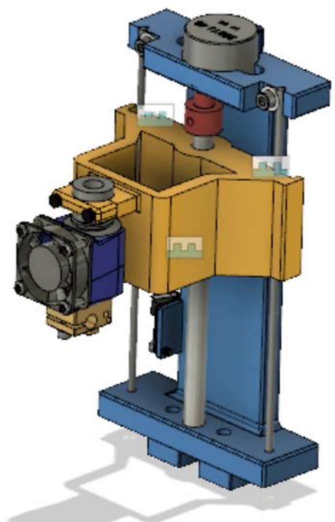

Figure 57: Isometric view of the I-shaped Z mechanism

In every sliding component an anti-backlash nut was added. An anti-backlash nut consists of a main nut body and a secondary ring that share the same thread form. There is a spring between the two components that force each part against opposing flanks of the screw thread. This spring takes up the clearance between all the components, therefore getting rid of the "wiggle room" or backlash [41]. These nuts gave more overall stability to the model and proved to make a big difference when testing the movement of the lead screw.

Figure 58: Anti-backlash nut [53].

Another very helpful part added to this iteration was threaded inserts for the screws that secure the rods in the base and in the Z axis. Threaded inserts are typically used when the object in which a threaded fastener is being installed is made of a soft material like plastic [40]. These helped keep the screw secured instead of the screw tearing in to the material which will eventually stop working.

Figure 59: Different sizes of threaded inserts [9]

This iteration let the team know that we were heading in the right direction. The base proved to be rigid and stable when it had applied force, and there was no backlash or wiggle anywhere in the prototype. The main problem found was that some tolerancing was off and the sliding pieces had too much friction for them to slide. Moving the pre-loads slightly down would improve this problem quickly, Leaving the rest for some final integrations to be made and reach our final prototype.

3.4 Final Prototype

The final prototype includes all of the changes that needed to be made in the past integrations, plus some additional printers that make the printer more interesting and adds to its functionality. This iteration brought the team to what would become the final product for the year.

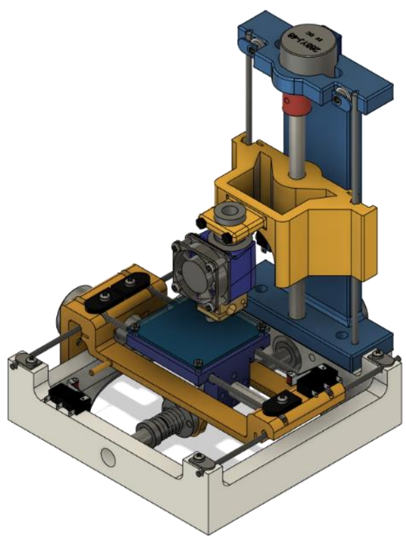

Figure 60: CAD model of final iteration of the 2021-2022 Palm Print design.

3.4.1 Assembly

Due to the portable nature of our printer, one of the main goals was for it to be user-friendly and easy to assemble and disassemble. The Z-axis connects into the X-Y base through slots on the base and are secured with M4 screws going into the bottom of the base with threaded inserts on the bottom side of the Z-axis piece. This provides the printer with the stability it requires to be accurate and portable at the same time. The part-count when the printer is disassembled is minimal which increases its possibilities to be a competitive product in the market.

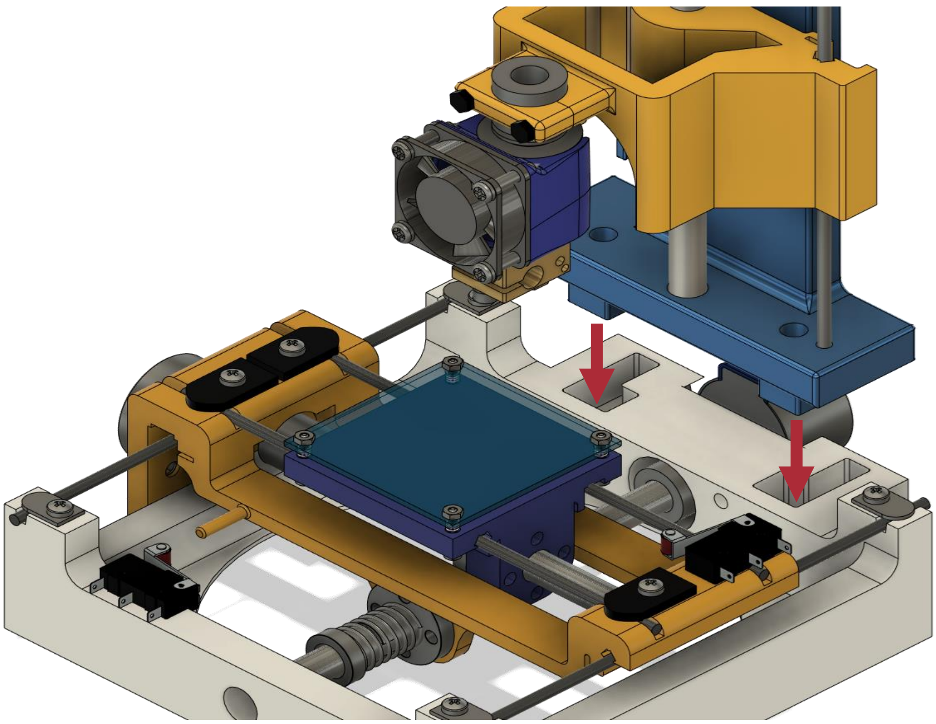

Figure 61: Diagram demonstrating how the Z-axis should be connected to the base of the printer

3.4.2 Design Review of Final Prototype

When designing the final prototype of the printer, we noticed problems with the coupler interfering with anti-backlash nut, which would decrease the print bed volume. To fix this issue, we move the motor for the Y-axis from the front of the printer to the back of the printer near where the Z-mechanism attaches to the base. The slider for the Y-axis was also edited to include the pin that will touch the limit switch, along with some adjustments to improve the tolerancing of some holes and parts that press fit together.

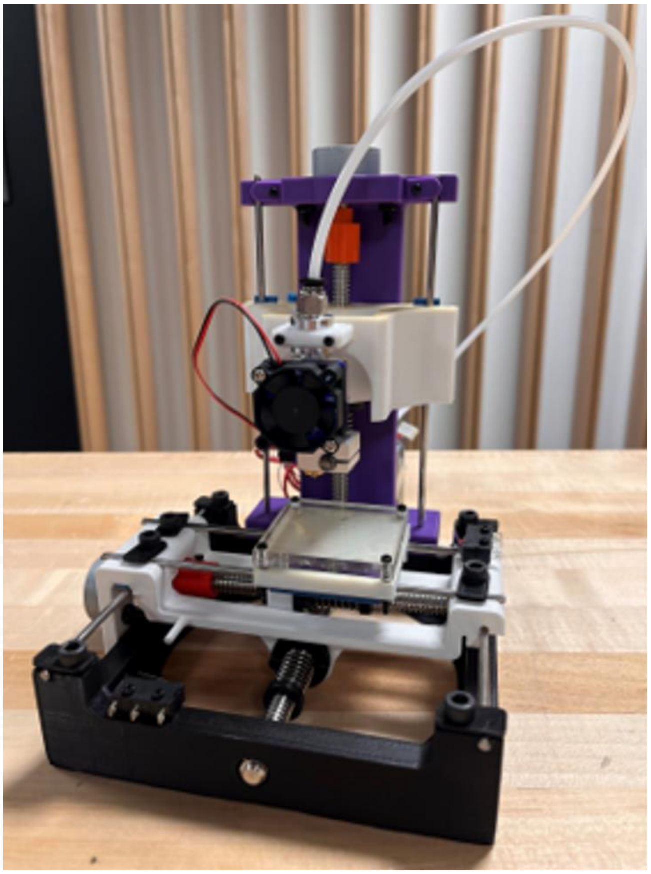

Figure 62: Assembled model of the 2021-2022 Palm Print design

Overall, all the changes and adjustments made for the final iteration of the design worked, as we were able to properly assemble the final prototype. The threaded inserts worked well for going around the issue of the screws not threading properly on the PLA, the hot-end had a good press-fit when it was being attached to the Z-axis slider. A print bed was cut out of acrylic and attached to the build plate with four M2 screws and nuts, along with four M3 springs, this design will allow for leveling the print bed, and replacing the acrylic if it is ever needed.

One of the edits that had the most notable change in the performance of the design was adding the cutouts to place a strip of Delrin in for every part of the rail system that meets the V-shaped groove and slots. This was to decrease the friction being created by the pre-load on the rails and slider. Delrin has a lower coefficient of friction than PLA, so this means that the slider has an easier time sliding on the Delrin strips than when it is touching the 3D printed parts. The addition of the springs to the print bed also adds the ability to level the print bed before prints, which is important in making sure there are no adhesion or print fails when trying to use the product.

Figure 63: Print bed with cutouts for Delrin strips and Delrin pre-loads

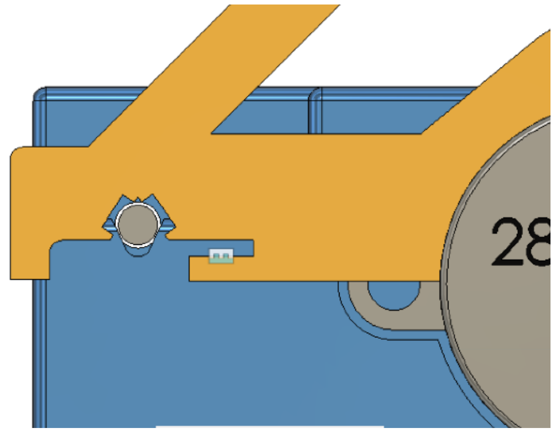

Figure 64: Z slider with cutouts for Delrin Strip and Delrin pre-loads

The final design of the prototype had a total height of 195.12 mm (7.68") and a base of 161.6 mm x 155 mm (6.36" x 6.10") and had a total weight of less than 1 kg (2.2 lbs). The entire product can be held in the palm of the user's hands, and can be quickly assembled and disassembled for easy storage and transportations.

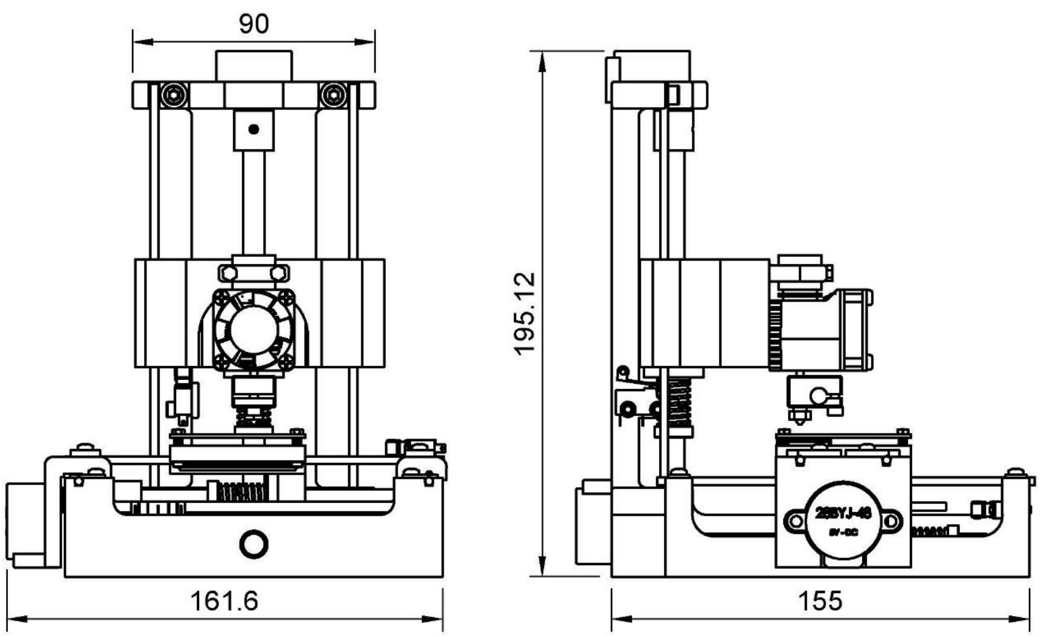

Figure 65: CAD drawing of the 2021-2022 Palm Print design with overall measurements (millimeters)

By including the CAD drawings, we intended to highlight its size and how compact the assembly is. These should help the next team to have a clear idea on how the different components interact together and to visualize potential improvements to the design.

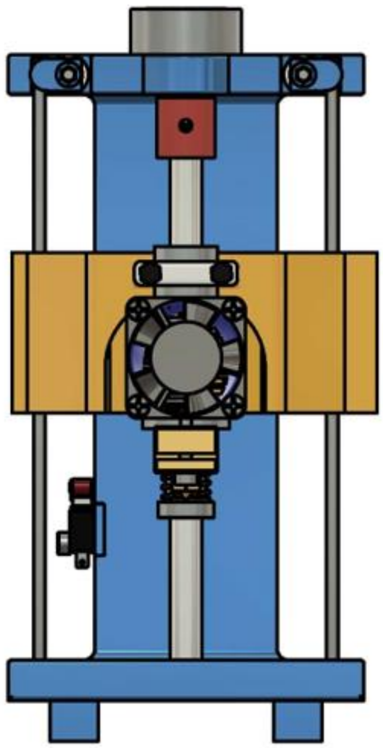

Figure 66: Front view of the Z-axis mechanism in CAD

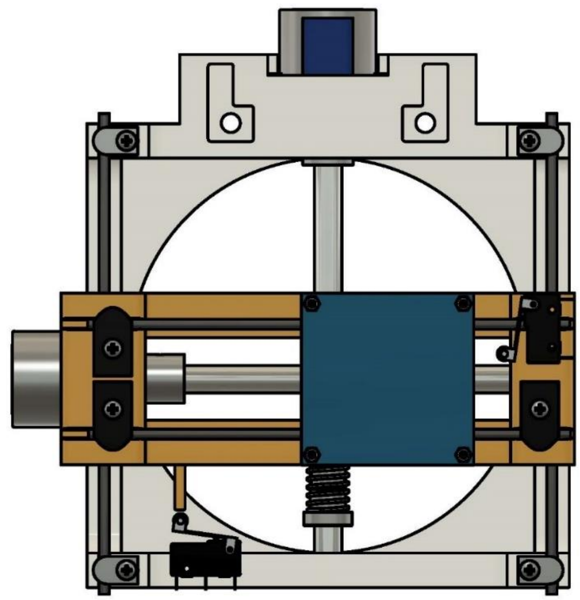

Figure 67: Top view of the Base (XY) mechanism in CAD

When it comes to manufacturing the 3D printing components designed by the team, most of them were printed with PLA plastic. However, the components that are supposed to be in constant contact with high temperatures were printed with Polycarbonate material. These components were the Z slider and the bed. Both these are close to the hot end and had the risk of melting if they remained made out of PLA. Polycarbonate reverts this risk by having a higher melting point of 230 to 260 degrees Celsius, which is around 50 degrees higher than PLA’s melting point.

4. Testing and Analysis

In order to ensure a prototype's desired functionality, a range of tests could be beneficial. However, due to time constraints the team was not able to complete any structural or modal analysis on the CAD assembly. The team was expecting to deliver these results utilizing Ansys software to determine strengths and developing areas of different components in the assembly.

In this section, we discuss the hardware set up and the software aid the team planned for the movement of the X, Y, and Z axes.

4.1 Motors

The 5V Arduino stepper motors are what is called a unipolar stepper motor. Unipolar stepper motors are often very popular among common consumers and are usually the cheapest way to get precise angular movements. They have a simple circuit and easy to operate, however, they are not powerful and slow. Another type of motors are, on the other hand, bipolar motors, which have the ability to go faster and output more power [3]. Unipolar motors could eventually be converted, and are able to be more efficient motors. Bipolar motors by doing some rewiring. After the rewiring is done, each motor is connected to the CNC shield into its respective pin labeled in the shield as X, Y, and Z for the different axes as seen in figure 68.

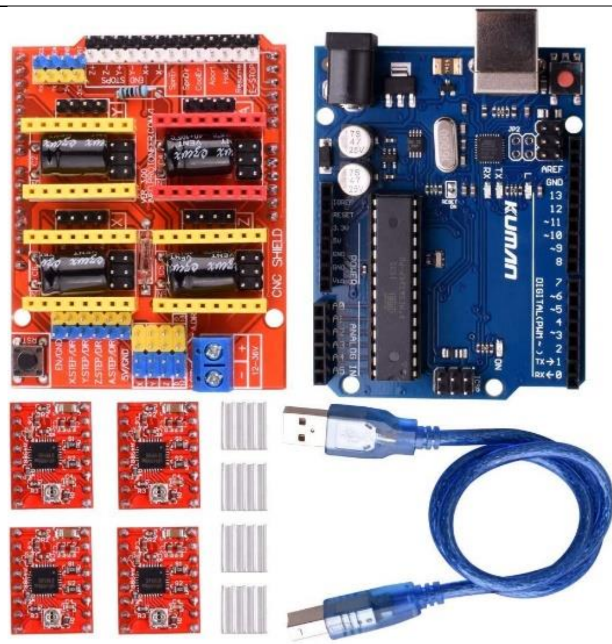

Figure 68: CNC shield and Arduino Uno microcontroller [3]

4.1.1 Wiring and Connections

By changing the wiring in these motors it is possible to convert them form unipolar stepper motors to bipolar. Unipolar configuration can produce 300g.cm of torque half stepped and 380g.cm when full stepped, when converted to a bipolar configuration (Figure 3) the motor produces 800g.cm of torque. This configuration also changes the motor driver being used, instead of a ULN2003 board to drive the stepper motor, an “H-Bridge” type of driver would be required [3]. Each motor is connected to their respective pins in the CNC shield like the one shown in Figure [68]

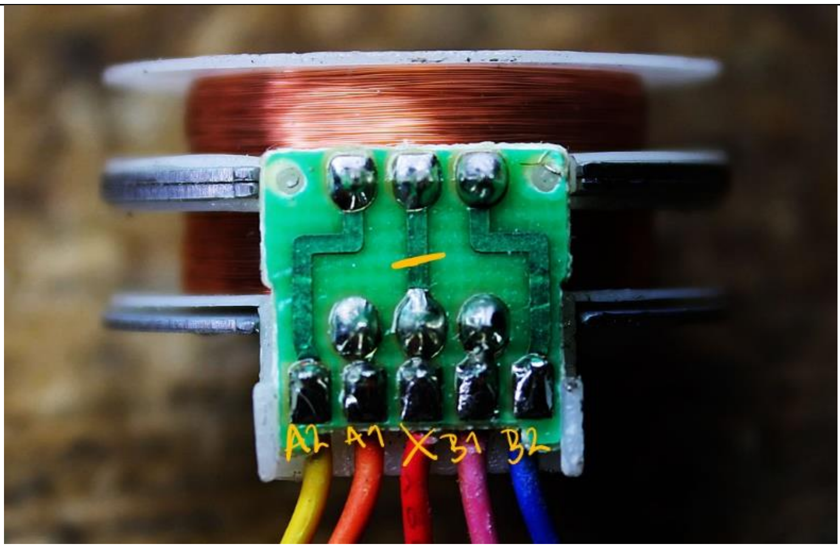

Figure 69: Wire configuration for 5V stepper motors [3]

4.1.2 Arduino and Code

The code is responsible for sending the information to the Arduino to be able to control the stepper motors in the X, Y, and Z axes on both different directions. The Arduino board has the CNC shield connected to it, which has each motor connected to their respective axis, as mentioned before in the section 2.2.6.

```
void setup() {
  // put your setup code here, to run once:

#define EN        8

//Direction pin
#define X_DIR     5
#define Y_DIR     6
#define Z_DIR     7

//Step pin
#define X_STP     2
#define Y_STP     3
#define Z_STP     4

}

void step(boolean dir, byte dirPin, byte stepperPin, int stps, int delayTime)

{


  digitalWrite(dirPin, dir);

  delay(10);

  for (int i = 0; i < stps; i++) {

    digitalWrite(stepperPin, HIGH);

    delayMicroseconds(delayTime);

    digitalWrite(stepperPin, LOW);

    delayMicroseconds(delayTime);


  pinMode(X_DIR, OUTPUT); pinMode(X_STP, OUTPUT);

  pinMode(Y_DIR, OUTPUT); pinMode(Y_STP, OUTPUT);

  pinMode(Z_DIR, OUTPUT); pinMode(Z_STP, OUTPUT);

  pinMode(EN, OUTPUT);

  digitalWrite(EN, LOW);
```

Figure 70: Fist page of the Arduino code

```
}
}
void loop(){
  //DRV8825
int delayTimeX=600; //Delay between each pause (uS)
int delayTimeY=600; //Delay between each pause (uS)
int delayTimeZ=600; //Delay between each pause (uS)
int stpsX=3000;// Steps to move
int stpsY=3000;// Steps to move
int stpsZ=3000;// Steps to move

  step(false, X_DIR, X_STP, stpsX, delayTimeX); //X, Clockwise

  step(false, Y_DIR, Y_STP, stpsY, delayTimeY); //Y, Clockwise

  step(false, Z_DIR, Z_STP, stpsZ, delayTimeZ); //Z, Clockwise

  delay(100);

  step(true, X_DIR, X_STP, stpsX, delayTimeX); //X, Not Counterclockwise

  step(true, Y_DIR, Y_STP, stpsY, delayTimeY); //Y, Not Counterclockwise

  step(true, Z_DIR, Z_STP, stpsZ, delayTimeZ); //Z, Not Counterclockwise

  delay(100);

}
```

Figure 71: Second page of the Arduino code

4.3 Analysis

When determining the total cost of the product, after the multiple iterations we printed, we had to weight the total mass of the 3D printed parts to calculate the price, and then add all of the purchased item to the sum. In total, the mass of the 3D printed PLA came out to 198.34 grams, and the PC parts weighed 74.2 grams. Using 3D printed material for a majority of the parts in this printer was a beneficial contribution for staying within the intended budget, as well as making the product light-weight.

Table 4: Bill of Materials for the 2021-2022 Palm Print: 3D Printer

Bill of Materials				
Item	**Quantity**	**Price (each)**	**Source**	**Item Total**
8mm Lead Screw	3	$6.50	Amazon	$19.50
T8 Anti-backlash Nut	3	$4.00	Amazon	$12.00
3mm Aluminum Rod	6	$0.77	Amazon	$4.62
5V Stepper Motor	3	$2.40	Amazon	$7.20
Threaded Inserts	1 Pack	$17.99	Amazon	$17.99
Screws/Nuts	1 Pack	$17.99	Amazon	$17.99
Limit Switch	3	$0.59	Amazon	$1.77
3D Printed Parts (PLA)	198.34 grams	$0.03	WPI Makerspace Store	$5.95
3D Printed Parts (PC)	74.2 grams	$0.05	WPI Makerspace Store	$3.71
Delrin Pre-Loads	1 Sheet	$3.99	Pick Punch	$3.99
3mm Springs	4	$0.80	Amazon	$3.20
12"x12" 1/8" Acrylic Sheet	1	$6.10	WPI Makerspace Store	$6.10
Hot-End	1	$9.99	Amazon	$9.99
Bowden Extruder	1	$10.49	Amazon	$10.49
Arduino and CNC Shield	1	$18.75	Amazon	$18.75
Total Product Cost				**$143.25**

5. Conclusion

The 2021-2022 Palm Print design successfully met most of the project goals that were given. There was a set budget at the beginning of the project of $150 total, and the team managed to keep the price of the model to $143.25 as shown in Table 5 below. This price could potentially come down with the research of smaller and cheaper components. However, it was noticed that when looking for smaller components the price of those parts may increase as they get smaller. The print volume ended up being 2” x2” x 1.8” which makes for an almost cubic shape. The Z axis could be redesigned slightly taller in order to make the shape completely cubic. If the build volume once to be made larger overall, the model should have to be scaled up.

The material that can be used by the printer is only PLA. In order to be able to print other materials the budget would increase by a considerable amount. The reason for this would be because some materials have the need for a heated bed, or an enclosure, and in addition the extruder would have to be changed. For this final prototype the bed was laser cut into a 2” x 2” plate. The plate is attached to the plate by screws with springs in the bottom to help with leveling the bed. Also, the wight of the printer was kept to 850g. There was no set weight that the team was aiming for, but 850g is light and easy to take anywhere, which is what Palm Print aims for.

The prototype would have been functional if not for time limit and some minor setbacks which will be discussed in the Recommendations section.

Table 5: Palm Print 2021-2022 printer specifications

Specifications	
Total Price	$143.25
Build Volume	2” x 2” x 1.8’
Printing Material	PLA
Print Bed Material	Removable Acrylic
Weight	850 grams

6. Recommendations

6.1 Future Considerations

The Palm Print 3D printer was a project that led the team to achieve multiple goals, however, several challenges arose along the way. Some of these challenges were related to some electrical components, parts cost, tolerancing and coding of the prototype. For each challenge, we recommend a feasible solution based on the team's experience.

6.1.1 Better Motors

When attempting to make the design even smaller, we ran into the problem of increased manufacturing costs. The ideal motors for this printer would be NEMA 14 motors, which have the appropriate torque and small size we are looking for; however, the NEMA 14 motors are about $20 more expensive than the motors used. In addition, the motor locations and mounting would need to be changed to incorporate the NEMA 14 motors into the design.

6.1.2 Decreasing Part Cost and Improving Size

As mentioned above, when the team attempted to shrink the model, it was evident that the smaller the pieces, the more expensive they got. This is common since the demand for smaller components is lower and some of them are even custom made. We recommend the next team continues to use standardized components that comply with the price and size requirements of the current project. Otherwise, discuss the possibility of adjusting the printer's price over its size or vice versa, so the team avoids meeting both specifications halfway.

6.1.3 Wire Management

In the last few years, the wiring of the electrical components has been very disorganized. This causes the wires to be free-floating, to entangle easily, and to risk the prototype's integrity by potentially causing an accident.

We recommend integrating wire placeholders to the design in order keep electrical connections and wires are always organized and in place.

6.1.4 Modifying Snap-fit Components

Tolerancing is one of the biggest challenges when it comes to manufacturing practices. In 3D printing, materials offer different mechanical properties and behaviors depending on the environment and parts post-processing. The team struggled with some parts shrinking and warping, affecting the calculated ±0.5 mm tolerancing for each part. This problem especially affected the functionality of snap fit components such as the motor couplers. Since some of them were a bit loose, the motors were unable to drive the leadscrews correctly.

We recommend that these tolerance dimensions are more precise for future iterations. The team learned that those components are sometimes a matter of trial and error.

6.1.5 Code Functionality

The team did not have enough time to have the Palm Print printer run a print utilizing the open-source programs. Even though it was possible to determine the Arduino code, it was challenging to have all the physical components working together with the help of Marlin and Pronterface.

We recommend the next team pays special attention to the coding part of the prototype with the guidance of the advisor or ECE/CS peers.

7. References

[1] *3D Printers with Different Kinematics: Comparison, Advantages and Disadvantages*. (n.d.). [Blog]. Digital Manufacturing Store Top 3D Shop. Retrieved October 15, 2021, from https://top3dshop.com/blog/3d-printer-kinematics-explained

[2] 3D Printing Concepts and 3D Printer Parts. (n.d.). *Leapfrog 3D Printers*. Retrieved September 3, 2021, from https://www.lpfrg.com/guides/3d-printing-concepts-and-3d-printer-parts/

[3] *28BYJ-48 Bipolar Mod*. (n.d.). Ardufocus. Retrieved March 22, 2022, from https://ardufocus.com/howto/28BYJ-48-bipolar-hw-mod/

[4] Ahart, M. (2019, June 3). *Types of 3D Printing Technology Explained*. ProtoLabs. https://www.protolabs.com/resources/blog/types-of-3d-printing/

[5] Alex M. (2017, December 15). *The 4 Types of FFF / FDM 3D Printer Explained (Cartesian, Delta, Polar)*. 3Dnatives. https://www.3dnatives.com/en/four-types-fdm-3d-printers140620174/

[6] Alexandrea P. (2017, October 5). *The Complete Guide to Fused Deposition Modeling (FDM) in 3D Printing*. 3Dnatives. https://www.3dnatives.com/en/fused-deposition-modeling100420174/

[7] All3DP. (2021a, October 28). *The Types of 3D Printing Technology in 2022*. All3DP. https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/

[8] All3DP. (2021b, December 27). *The Best 3D Printer Filament Types of 2022*. All3DP. https://all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament/

[9] *Brass Threaded Inserts*. (n.d.). Retrieved March 4, 2022, from https://www.amazon.com/Swpeet-Embedment-Hydraulic-Injection-Assortment/dp/B08YYGRCBG/ref=sr_1_8?keywords=m6%2Binserts&qid=1639354827&sr=8-8&th=1

[10] Carolo, L. (2020, May 23). *3D Printer Axis: The Basics – Simply Explained*. All3DP. https://all3dp.com/2/3d-printer-axis-the-basics-simply-explained/

[11] Clark, E. (2016, May 23). 18 3D Printer Filament Types And Uses Comparison Guide. *AllThat3D*. https://www.allthat3d.com/3d-printer-filament/

[12] Collins, D. (2019, March 26). *When do synchronous belts need flanged pulleys?* Linear Motion Tips. https://www.linearmotiontips.com/when-do-synchronous-belts-need-flanged-pulleys/

[13] Conradie, D. (2021, August 3). Strangest Upside-Down 3D Printer Fits In A Filament Box. *Hackaday*. https://hackaday.com/2021/08/03/strangest-upside-down-3d-printer-fits-in-a-filament-box/

[15] Coryl. (2016, March). *Introducing Galil's New H-bot Firmware*. Galil. https://www.galil.com/news/whats-new-galil/white-paper-introducing-galils-new-h-bot-firmware

[16] *Creality 3D Endstop Switch Limit Switch for Ender-3 V2 3D Printer Part*. (n.d.). Retrieved February 23, 2022, from https://alexnld.com/product/creality-3d-endstop-switch-limit-switch-for-ender-3-v2-3d-printer-part/

[17] Crease, A. (n.d.). *Basic Pulley Mechanisms*. Instructables. Retrieved October 8, 2021, from https://www.instructables.com/Basic-Pulley-Mechanisms/

[18] Diallo, B. (n.d.). 3D Printer Filament Types and Uses. *Leapfrog 3D Printers*. Retrieved September 21, 2021, from https://www.lpfrg.com/guides/3d-printer-filament-types/

[19] Doris. (2016, November 7). *PocketMaker: $99 Mini FDM 3D Printer Now Available on Indiegogo*. 3Printr.Com. https://www.3printr.com/pocketmaker-99-mini-fdm-3d-printer-now-available-indiegogo-4643850/

[20] *Ender 3 Pro 3D Printer*. (n.d.). Creality. Retrieved December 15, 2021, from https://www.creality3dofficial.com/products/creality-ender-3-pro-3d-printer

[21] filament2print. (2020, July 6). *How to choose the correct hotend*. Filament2print. https://filament2print.com/gb/blog/96_How-to-choose-the-correct-hotend.html

[22] Fisher, T. (2022, February 14). *What Is Firmware?* Lifewire. https://www.lifewire.com/what-is-firmware-2625881

[23] *Foldable S2: World's First Foldable 3D Printer*. (2021, February 2). Kickstarter. https://www.kickstarter.com/projects/2140777456/foldable-s2-worlds-first-foldable-3d-printer

[24] *FoldaRapX - RepRap*. (2020, December 3). https://reprap.org/wiki/FoldaRapX

[25] Grames, E. (2021, September 15). *CoreXY 3D Printer Design: Why It Makes a Difference*. All3DP. https://all3dp.com/2/corexy-3d-printer-is-it-worth-buying/

[26] Gross, B. C., Erkal, J. L., Lockwood, S. Y., Chen, C., & Spence, D. M. (2014). Evaluation of 3D Printing and Its Potential Impact on Biotechnology and the Chemical Sciences. *Analytical Chemistry*, *86*(7), 3240–3253. https://doi.org/10.1021/ac403397r

[27] Hanson, M., Jennings, A., Hill, J., & Weatherbed, J. (2022, March 4). *Best 3D printers of 2022: Top choices for work and home use*. TechRadar. https://www.techradar.com/best/best-3d-printers

[28] Heason. (n.d.). *What is a Lead Screw?* Heason. Retrieved December 10, 2021, from https://www.heason.com/news-media/technical-blog-archive/what-is-a-lead-screw-

[29] Hodgkins, K. (2016, November 8). *If you can fit it in your pocket, you can 3D print with the PocketMaker*. Digital Trends. https://www.digitaltrends.com/cool-tech/pocketmaker-3d-printer-indiegogo/

[30] Hullette, T. (2021, March 20). *Direct Drive vs Bowden Extruder: The Differences*. All3DP. https://all3dp.com/2/direct-vs-bowden-extruder-technology-shootout/

[31] Khalid, H. (2019, December 13). What Are The Uses Of The Standard 3D Printer Enclosures? *Prototype Info Sharing Blog*. https://prototypeinfo.com/standard-3d-printer-enclosures-uses/

[32] *Lead Screw*. (n.d.). IQS Directory. Retrieved November 12, 2022, from https://www.iqsdirectory.com/articles/ball-screw/lead-screws.html

[33] *Linear Robotics Application Photos*. (n.d.). Macron Dynamics. Retrieved October 25, 2021, from https://www.macrondynamics.com/linear-robotics/application-photos

[34] MachMotion. (2018, January 2). What is backlash? *MachMotion*. https://machmotion.com/blog/what-is-backlash-and-how-to-correct-it/

[35] *Marlin 3D Printer Firmware*. (2022). [C++]. Marlin. https://github.com/MarlinFirmware/Marlin (Original work published 2011)

[36] Martin. (2020, September 22). *CoreXY vs. H-Bot: Which System is Better for a 3D Printer?* The 3D Printer Bee. https://the3dprinterbee.com/corexy-vs-hbot/

[37] McCollum, W. (2021, December 17). CoreXY vs. HBot: What's the Difference? *For 3D Print*. https://43dprint.org/corexy-vs-hbot/

[38] McIl, A. (2021, September 10). *Main Parts of FDM 3D Printers Explained*. https://apm-designs.com/3d-printer-main-components/

[39] Metz, D. (2020, August 1). *Arduino CNC Shield: Buyer's Guide*. All3DP. https://all3dp.com/2/arduino-cnc-shield-buyers-guide/

[40] Monroe Engineering. (2019, June 1). What Is a Threaded Insert? *Monroe Engineering*. https://monroeengineering.com/blog/what-is-a-threaded-insert/

[41] Nook, C. (n.d.). *How to Choose Anti-Backlash Nut*. Helix Linear Technologies. Retrieved December 11, 2021, from https://www.helixlinear.com/blog/lead-screws/how-to-choose-an-anti-backlash-lead-screw-nut/

[42] O'Connell, J. (2021, September 12). *3D Printer Heatsink: How to Prevent Heat Creep*. All3DP. https://all3dp.com/2/3d-printer-heat-sink-creep/

[43] O'Connell, J. (2022a, April 18). *3D Printer Bed: How to Choose Your Build Plate/Surface*. All3DP. https://all3dp.com/2/3d-printer-bed-how-to-choose-the-right-build-plate/

[44] O'Connell, J. (2022b, April 23). *The Types of FDM 3D Printers in 2022: Cartesian, CoreXY, Delta, & More*. All3DP. https://all3dp.com/2/cartesian-3d-printer-delta-scara-belt-corexy-polar/

[45] *Original Prusa MINI+*. (n.d.). PRUSA Research. Retrieved December 10, 2021, from https://www.prusa3d.com/product/original-prusa-mini-kit-2/

[46] *Polar 3D Printer and Polar Cloud*. (n.d.). Sargent Welch. Retrieved October 12, 2021, from https://www.sargentwelch.com/store/product/21104232/polar-3d-printer-and-polar-cloud

[47] Polka, D. (2001, August 22). *Understanding Electronic Motor Drives*. Machine Design. https://www.machinedesign.com/motors-drives/article/21832533/understanding-electronic-motor-drives

[48] *Pronterface Manual.pdf*. (n.d.). Retrieved April 28, 2022, from http://robotix.ah-oui.org/user_docs/2003/pronter-manual.pdf

[49] QUALUP SAS. (n.d.). *Qu3-HT-2022 High Temperature 3D Printer*. QUALUP SAS. Retrieved April 27, 2022, from https://qualup.com/en/index.php

[50] Rosencrance, L. (n.d.). *What is Software?* SearchAppArchitecture. Retrieved March 7, 2022, from https://www.techtarget.com/searchapparchitecture/definition/software

[51] Simplify3D. (n.d.). *Ultimate 3D Printing Material Properties Table*. Retrieved November 7, 2021, from https://www.simplify3d.com/support/materials-guide/properties-table/

[52] Sink, A. (2022, April 3). *Best 3D Printers 2022: FDM, Resin and Sub-$250 Models*. Tom's Hardware. https://www.tomshardware.com/best-picks/best-3d-printers

[53] *T8 Anti Backlash Nut*. (n.d.). Retrieved December 7, 2021, from https://www.amazon.com/dp/B07XYQTR65/ref=cm_sw_r_cp_api_glt_fabc_JWCN36B9NQFG2ZVWQ73T?th=1

[54] *What is Arduino?* (2018, February 5). Arduino. https://www.arduino.cc/en/Guide/Introduction

[55] *What is firmware?* (n.d.). WhatIs.Com. Retrieved March 7, 2022, from https://www.techtarget.com/whatis/definition/firmware

[56] *What is Marlin?* (2022, March 30). Marlin Firmware. https://marlinfw.org/docs/basics/introduction.html

[57] Yanev, K., & Seguin, G. (n.d.). *Printrun: Pure Python 3d printing host software*. Retrieved March 4, 2022, from https://www.pronterface.com/

Kris, A. (2019, December 13). What Are The Uses Of The Standard 3D Printer Enclosures? *Prototype Info Sharing Blog*. https://prototypeinfo.com/standard-3d-printer-enclosures-uses/