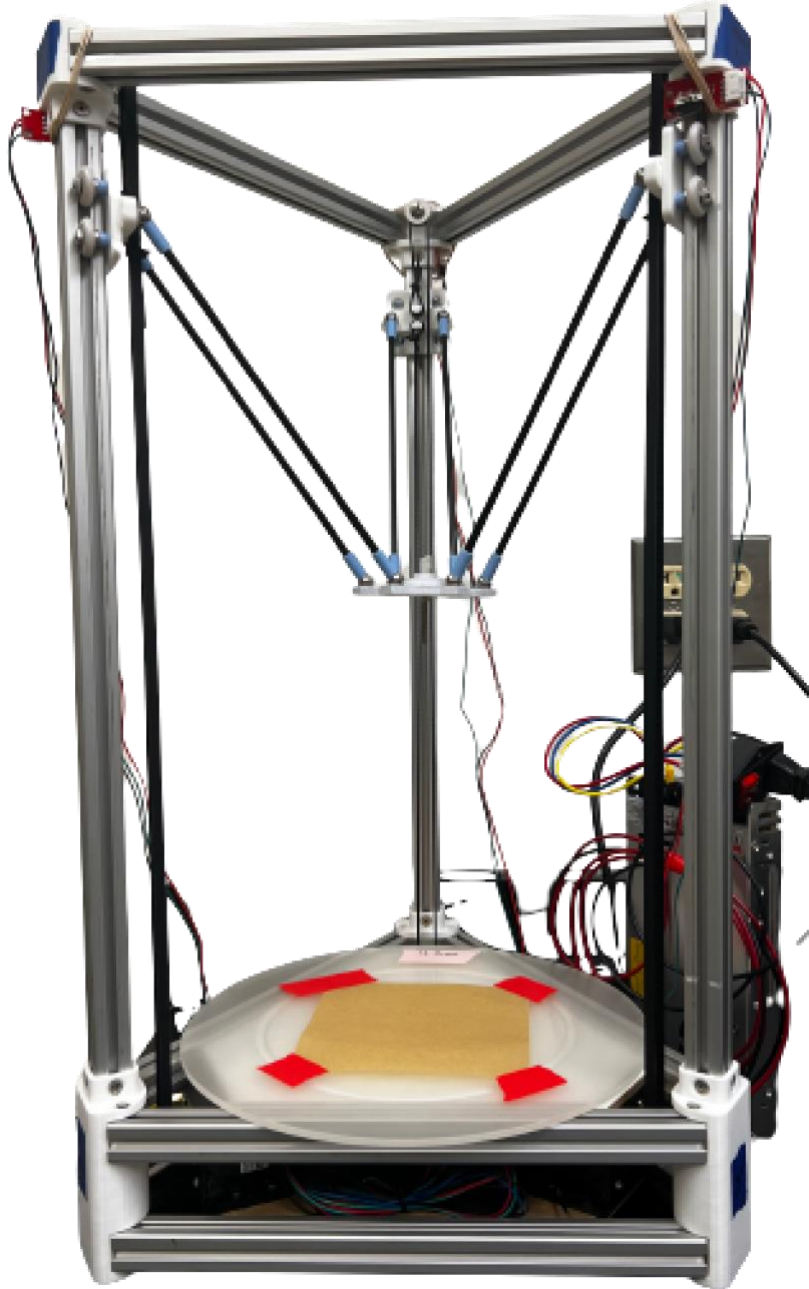


# DEVELOPING A 3D FOOD PRINTER



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# Developing a 3D Food Printer

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# WPI

A Major Qualifying Project

WORCESTER POLYTECHNIC INSTITUTE

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August 2022 – March 2023

## **Abstract**

This project aims to merge three different disciplines, computer science, robotics, and mechanical engineering, to further develop a student-made 3D Food Printer (3DFP). Contributions from computer science and robotics will generate a software package that will facilitate the printer's function, whereas the mechanical contributions will ensure the machine is structurally sound and produce desirable prints through a material science lens.

3D Food Printing (3DFP) is a new and innovative approach to additive manufacturing with promising applications in nutrition, health fields, and military fields. 3DFP offers the user the ability to customize their food items by adding nutrients and vitamins to enhance the nutritional properties of their meals. Due to the infancy of this technology, readily available machines are lacking in many areas, specifically in user operations, both mechanically and in user interfaces. Thus, this project aims to fill these gaps and improve these criteria. Due to the large scope of this project, the project will consist of two distinct parts, the mechanical component – the building of the 3DFP, and the software side – coding the 3DFP to run additive manufacturing commands.

## Acknowledgments

We would like to thank the following people for assisting us with our project; our work would not have been successful without their participation.

- **Julia Toplyn:** For being a crucial part of our project and providing stellar mechanical engineering support.
- **Professors Danielle Cote and Rodica Neamtu:** For being our MQP advisors and challenging our team. Each week during our meetings, they provided us with meaningful feedback on our progress and pushed us to achieve beyond expectations.
- **Cem Aygul:** For being an amazing resource to our team by helping us make critical decisions and teaching us about his 3D printing experience.

## Authorship

It is important to note that the composition of this report was communal; however, the following authorship depicts the primary contributions to each of the sections. Julia Toplyn will continue with more mechanical research after the submission of this paper.

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Background		
Movement Types of 3D Printers	Julia Toplyn	Ashley Burke, Nupur Shukla
3D-Food Printers at WPI	Julia Toplyn & Nupur Shukla	Ashley Burke, Nupur Shukla
3D Printing Process Workflow	Ashley Burke	Nupur Shukla, Julia Toplyn
Our Current 3D Food Printer	Julia Toplyn	Ashley Burke, Nupur Shukla
Methodology		
Project Management	Nupur Shukla	Ashley Burke, Julia Toplyn
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Extruder	Julia Toplyn	Ashley Burke, Nupur Shukla
Investigating User Interface	Nupur Shukla & Ashley Burke	Julia Toplyn
YouTube Tutorials	Nupur Shukla	Ashley Burke, Julia Toplyn
Conclusion and Future Recommendations		
Extruder	ALL	ALL
Endstops	ALL	ALL
Next Steps	ALL	ALL

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## 1.0 Introduction

Due to the infancy of 3D-food printing, there are still many areas where the technology has not been fine-tuned, or even addressed. This project aims to produce a 3D-Food Printer (3DFP) that tackles the area of usability. The want to fill this gap derives from student experiences with the currently available machines, which, while effective devices, fall short in their overly complex and finicky user interfaces. While 3D food printing has many applications, as outlined in the figure below (Figure 1), they should be intuitive and easy to use regardless of the device's use case.

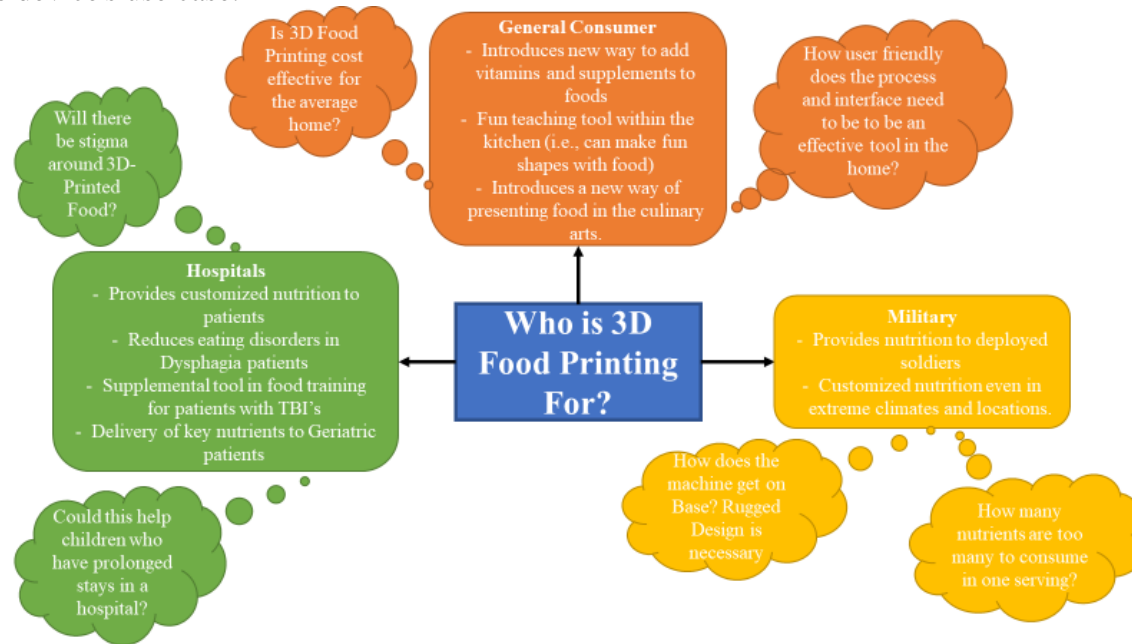


Figure 1 - 3D Food Printing User Case Study

It was observed that the machines' confusing interfaces and overall complex structures were prohibitive in continuing 3DFP research, as more time was spent cleaning the machine than printing. Due to this cumbersome nature, it was feared that many users would be deterred from the technology. The idea of creating a 3DFP that we will use in this project emerged through the work done by Julia Toplyn. The 3DFP is outlined in more detail in Section 2.4 Our Current 3D Food Printer. All structural and mechanical functions were designed and fabricated prior to this MQP.

The 3DFP's design is very different from most 3DFP available on the market. The Linear Delta style printer utilizes three vertical axes (rather than X, Y, and Z, as seen in Cartesian) set in a triangle, so that vertical movement moves the effector plate (horizontal plate that the nozzle is mounted) in 3-dimensional space. The following figure (Figure 2) provides a visual aide to the differences between a Cartesian and Delta printer. The Delta printer facilitates faster print times, an area where the student felt improvements were crucial. The linear delta design not only facilitates faster print times but also allows the extruder to be a separate system, connected via a tube, thus reducing the amount of clean-up required between prints, another crucial improvement area.

This interdisciplinary capstone aims to bring "life" to the structural and mechanical components of the 3DFP through a user-friendly interface for controlling the device. By introducing a simple user interface that allows the user to control critical mechanical and material properties of the 3DFP, we hope to make 3D food printing less daunting and more accessible.

Numerous challenges are associated with accomplishing the goal of this project. In general, trying to make hardware and software components work together is a daunting task, but it becomes even more difficult when concepts are unfamiliar. Coming into this capstone, we had limited knowledge of 3D Food Printing. Therefore, the main challenge of this project was

researching the proper tools to use for our custom-made 3D printer. Once we had identified the correct tools and configurations, testing became the next hurdle to overcome. Testing our configurations against the printer helped us identify issues in the code and allowed us to tweak certain dimensions, ensuring that the printer executed the commands accurately.



*Figure 2 - Comparison of Cartesian and Linear Delta Printers*

## **2.0 Background**

3-Dimensional Printing, or 3D printing for short, is a technology that has been around for nearly 40 years. The technology creates 3-dimensional objects by laying down material in layers, one on top of the last, like one would stack Legos. Due to this being such an active area for research over the past four decades, 3D printing has significantly developed in many other areas (apart from the traditional printing with plastics). In addition to the traditional printing of plastic, new types of printing have emerged, such as metal printing (using

metal powders and different techniques to fuse the particulate), construction printing (using concrete or similar materials to build homes and other structures), and lastly, where our project is situated, 3D Food Printing (3DFP) (Miller, 2022).

3DFP is very new; it is still very much in its infancy. Many individuals are working to determine areas where 3DFP could be most beneficial. Currently, 3DFP is utilized by deployed troops, children in hospitals, and patients with dysphagia (individuals with difficulty swallowing) (Toala & Mateo, 2022). Our project will situate itself in furthering the research on 3DFP, specifically, evaluating how consumers use the machine and how to generate a positive relationship with the technology.

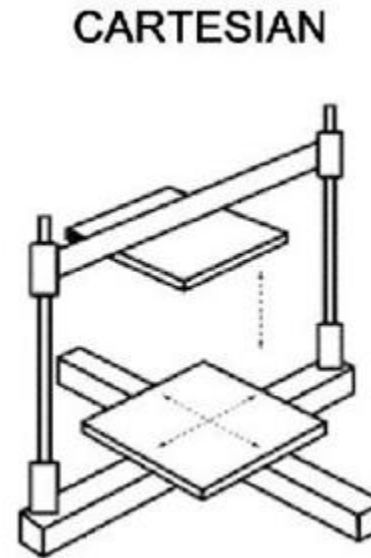
## 2.1 Movement Types of 3D Printers

Similar to the way different disciplines have adapted 3D printing into their research, like printing organs, or construction and printing houses and other structures, there have been considerable advancements in developing different “types” of printers. By “type” of printers, we refer to mechanical and electrical movements rather than their applications. The following section by no means introduces every type of printer but does address the most common types and the type most pertinent to this project.

### 2.1.1 Cartesian

Cartesian printers use cartesian coordinates, or X, Y, and Z axes. These printers are the most common in most use cases. The “traditional” cartesian printer, has a nozzle (the component that extrudes filament) mounted to the Z axis allowing the build-plate to remain stationary as the nozzle traces the file shape in the XY axes and raises on the Z axis to begin a new layer. In some cases, the build plate traverses the Z axis rather than the nozzle; however, this is less common. Please refer to Figure 3 for a summary of “typical” cartesian printer movement.

There are two common variants of cartesian printers, CoreXY and CoreXZ printers. These variants are often more specialized for different printing purposes (i.e., deviating from plastics as a primary printing material). CoreXY printers were introduced in 2013, where the main objective was reducing the number of



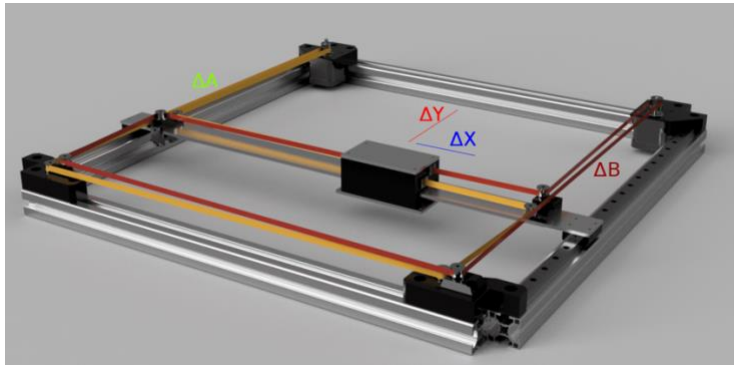
*Figure 3 – Visual Representation of the “Traditional” Cartesian Printer Movement*

*(The 4 Types of FDM 3D Printer Explained (Cartesian, Delta, Polar & Scara) - 3DSourced, 2020)*

heavy components the printer must move. The printers are often cube-shaped and rely on belts and pulleys to move the build plate and nozzle (arguably, more so than the traditional cartesian printer outlined above). Generally, these types of printers reduce the print times and offer more compact footprints than the “traditional” cartesian printers (more cubical rather than tall

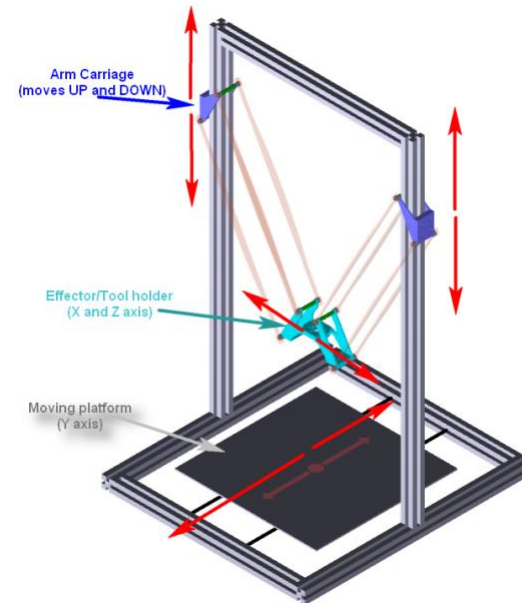
rectangles). However, to achieve this, the user often needs a larger understanding of 3D printer mechanics (i.e., tensioning belts and assembling unique frames and functions) (*CoreXY Vs Cartesian*, 2021). Figure 4 presents the essential belt functions that separate CoreXY printers from their more “traditional” counterparts.

The second variant of a cartesian printer is the CoreXZ printer. This printer type uses two vertical supports and two arm carriages that move the tool head up and down the Z axis and traverse the X axis while the build plate moves on the Y axis (*CoreXZ | Parallel Arms Motion Platform*, n.d.). This design reduces inertia felt in the system, which results in faster print times than with a traditional cartesian printer. The XZ printer type is also less limited by how large the device can be, as the dual carriage set-up can facilitate taller devices. Figure 5 provides a visual for the components and movements associated with a Core XZ printer.



*Figure 4 – CoreXY Printer Movement (Belt Specific)*

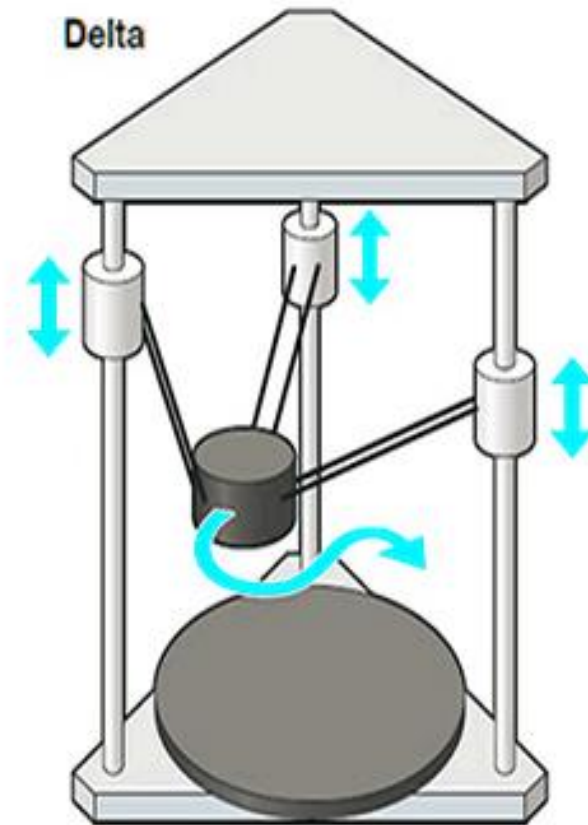
(ADMIN, 2017)



*Figure 5 – Core XZ Movement Example  
(CoreXZ | Parallel Arms Motion Platform, n.d.)*

### 2.1.2 Delta

Another category for printer movement is delta printers. These printers are less common than cartesian printers; however, they have become more widely available in recent years. Delta printers use three vertical axes to move three arms. These arms are connected to the effector plate or the platform where the tool head is mounted. Due to the variation of movement, Delta printers use trigonometric features to produce coordinates rather than X, Y, and Z coordinates. Delta printers' primary advantage over cartesian printers is their ability to print vertical parts much faster than cartesian printers (*CoreXZ | Parallel Arms Motion Platform*, n.d.). Figure 6 provides a helpful visual aid to a Delta printer's movement and basic design.



*Figure 6 – Delta Printer Movement Diagram  
(CoreXZ | Parallel Arms Motion Platform, n.d.)*



## 2.2 3D-Food Printers at WPI

There are two 3D Food Printers on campus. One of these printers, the Engine SR, was purchased by WPI Professor Danielle Cote. The second printer on campus, the Foodini, is on loan to us through a partnership with the Natick Soldier Center. We are incredibly thankful to have the opportunity to use these machines to further our research capabilities in 3DFP.

### 2.2.1 Foodini

Our first machine for our research was the Foodini by Natural Machines. This machine was designed to introduce 3DFP to a larger audience of general consumers than researchers. The device is an enclosed cartesian printer that offers up to five “capsules”<sup>1</sup> for food products. The Foodini allows the user to create material profiles on the machine and offers a calibration process for fine-tuning each printing material (*Natural Machines Foodini - How It Works*, n.d.). The device also boasts a large cloud of pre-made designs or an onboard design maker for more creative individuals. Please refer to Figure 7 for a visual of the Foodini currently in our lab.

While the device offers many impressive features, students have found that the features are not always precise or functional. Specifically, the calibration test for each material is a beneficial function in theory. However, in practice, it often took at least three attempts for the calibration test to run from beginning to finish, and often did not save or update the changes made by the user. Furthermore, the machine’s onboard designer feature did not offer the same features observed in desktop CAD (Computer Aided Drafting) software. It was incredibly difficult to make test files crucial in observing machine functions. Printing a 1cm x 1cm x 1 cm cube allows a user to observe the dimensional

accuracy of a device, which allows users to create calibration curves to increase dimensional accuracy (if the cube is not dimensionally accurate). The onboard interface made it impossible to create a 1cm x 1cm x 1cm cube. The software did not allow us to select precise measurements, nor did the onboard software allow us to upload our files to work around this.



Figure 7 – Foodini by Natural Machines

Therefore, the Foodini machine did not fit our needs for our previous research opportunities. However, these shortcomings have allowed us to create focus on the user interface for the 3DFP we will create by the end of this project.

### 2.2.2 Engine SR

The second 3DFP at WPI is the Engine SR by Hyrel3D. This machine is more focused on research and development. The Engine SR is a traditional “Fusion Deposition Modeling” (FDM) printer which builds an object fusing each layer together. However, it has 3D Food Printing nozzle attachments that allow this machine to be used to further our 3DFP research. The device

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<sup>1</sup> Natural Machines refers to their proprietary metal syringes as “Capsules.” The capsules hold the food material the user wishes to use to print.

can print from 4 syringes (equivalent to the Foodini’s “capsules”) at once (admin, n.d.). Please see Figure 8 for a visual of the device in our laboratory.



*Figure 8 – Engine SR by Hyrel3D*

The system offers greater control over functions and file management than the Foodini. The firmware allows the user to

execute more “traditional” 3D printer functions, such as homing, zeroing the Z height offset, preview the G-code path. The Engine SR also allows the user to upload their files made by desktop CAD software, which offers more precise and flexible options for files and machine movement. These functions have proven to be crucial to our research and have allowed us to create more extensive tests than possible with the Foodini.

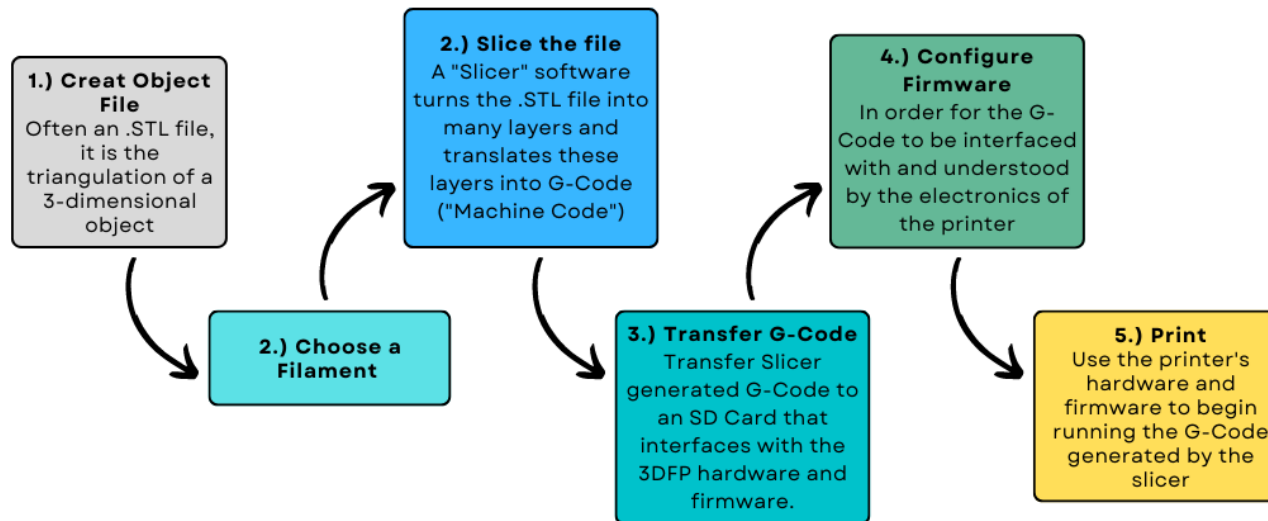
However, there are areas where the Engine SR is not user-friendly, even for those more familiar with the 3D printing process. The user interface is the primary area where the machine is difficult to use. The device uses a touch screen that presents the user with different pages, such as a homing page, an onboard slicer, onboard G-code editing capabilities, and a printing monitoring page. While these features are usually helpful, they are not executed well on this device. We found it incredibly difficult to view and use the slicer as an onboard function and often used a desktop slicer to generate our files. We also found the homing page to be finicky and often did not execute functions in the correct order or at all.

While the Engine SR allowed us to create more precise and valuable tests for advancing 3DFP research, the overall user experience did not engender excitement towards continuing to use the device. These experiences have also shaped the trajectory of this project, as it has highlighted how critical having an intuitive and effective user interface is for advancing 3DFP research.

### 2.3 3D Printing Process Workflow

Several steps must be taken to make a 3D printer produce a 3D object. Since our printer does not have any heating elements, ground-up food items in a viscous form are used as the printing filament. Only after the food has been printed does it get cooked. Due to the overlap in methods used to print food ordinary objects, the 3D food printing process follows the same workflow process as printing any other object. With the help from BCN3D, we created Figure 9 to highlight the general steps needed to print an item (BCN3D, 2020). The following subsections go into further detail about each step of the flowchart.

## The 3D Printing Process



*Figure 9 – Summative 3D Printing Flowchart*

### 2.3.1 Generating an Object File

To print an object using a 3D printer, one must first produce an object file, generally using CAD (computer-aided design) software. With this software, you can draw the object you wish to be printed and download it as an object file. The file then encodes the geometry of the 3D Object through polygonal meshes, as seen in Figure 10.

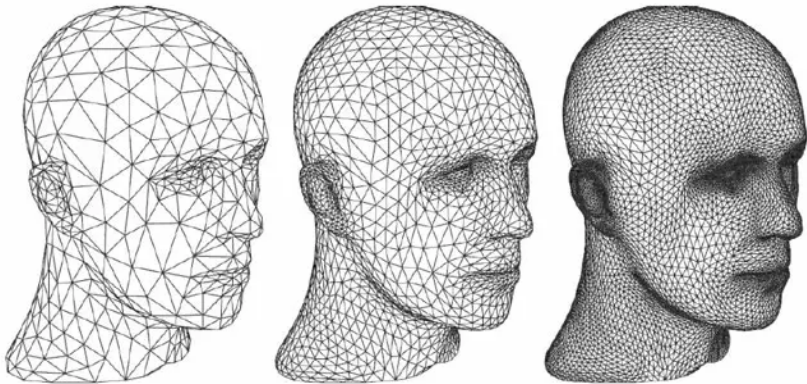


Figure 10 – Example of Polygonal Meshes (Triangulation)  
(Dwamena, n.d.-a)

The two main file types that can be used to store 3D objects are OBJ (Wavefront object) files and STL (standard tessellation language) files. STL files (.stl) are the most common 3D file type due to their simplicity and small size. While STL files are simpler, OBJ files (.obj) tend to have a higher resolution and more accurately represent texture (*STL vs. OBJ vs. IGES vs. STEP: An Overview of 3D File Types / Jaycon Systems, n.d.*). While both file types can be used when printing food, due to the in-necessity of fine detail when it comes to 3D printing food, STL files are more commonly used. this comparison is visually represented in a table shown in Table 1.

Table 1 – Comparison of .STL and .OBJ Filetypes

(*STL vs. OBJ vs. IGES vs. STEP: An Overview of 3D File Types / Jaycon Systems, n.d.*)

Filetype	Overview	Level of Detail	Application
STL	STL files store objects as sets of vertices joined by edges	Medium-Low	3D Printing

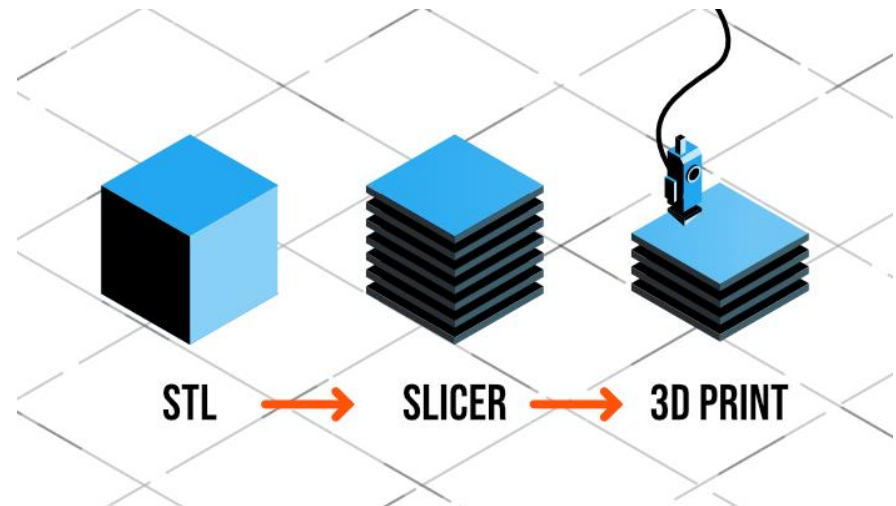
	to make triangular faces.		
OBJ	OBJ files store 3D information as a list of vertices joined by edges, and unlike STLs, they support polygonal faces that allow for a closer representation of the original geometry.	Medium	3D Printing (it includes object color and texture information)

### 2.3.2 Choosing a Filament

In 3D printing, the extruder is the part of the machine that holds the filament, or the material being printed with. There are many types of filaments that can be used, but several factors must be considered when deciding which one is best for the print job. When trying to print food, rather than looking at the purity or the mechanical properties of the material, like one would with metal or plastic, the filaments viscosity (how thick something is) is considered. If the filament is too viscous, such as water, the 3D printed object would not be able to hold its shape and would just form a puddle. If the filament is too thick, such as a dough mixture having ground up nuts, the extruder may not have the strength to push the filament through the syringe (Toala & Mateo, 2022). It is important to find a balance between too thick and too thin, while still trying to produce the desired product.

### 2.3.3 Slicing the Object File

When a printer prints a 3D object, it does so by printing a single layer (a “slice”) at a time, layering them on top of each other until the final product is produced. As the name suggests, a slicer is a program that essentially takes a 3D object and “cuts” it into many horizontal 2D “slices” that is later printed one at a time. A slicer also reduces the amount of user required inputs such as printer dimensions, start and end G-code conditions, simplifying the creation of a print file. A visual representation of this can be seen in Figure 11.



*Figure 11 – Visual Representation of a Slicer’s Functions*  
("What Is the Role of Slicing in 3D Printing?," 2021)

Before the program slices the 3D object, several parameters must be set within the software to tell the printer how to print. Some of these parameters include print speed, layer height, fill density, wall thickness, retraction, temperature, and more (IV. *Slicing. As Lulzbot Says, "slicing Software... | by Garrett Spiegel / 3D Printing in O&P | Medium*, n.d.). The slicing settings must be adjusted every time it is used for a different filament or 3D object.

### 2.3.4 Transferring the G-code

Once the slicer generates the G-code file (.g file) needed to print the desired 3D object, the user must then upload the file to the printer. G-code, generally produced by a slicer program, is a programming language. G-code files have commands that 3D printers can understand. The G-code commands hold movement settings, heating elements, printer parameters, etc. Transferring the code to the printer can be done in the following ways.

#### *(Micro) SD Card:*

One of the most common ways to transfer G-code to a 3D printer is through a (micro) SD card. Almost every printer in the industry has an SD card slot. The type of storage device is restrained by the electrical components (i.e., what the motherboard has and what type of physical input it can read). In this approach, the G-code file produced by the slicer is downloaded and saved onto the SD card, and then inserted into the printer. This approach is exceedingly popular due to its simplicity and effectiveness without the need for different devices or applications. Despite the benefits in using an SD card, they can easily be broken (Dwamena, n.d.-b).

#### *USB Cable Connection:*

A less common method of transferring G-code to a 3D printer is through a USB cable connection. With this method, a computer is connected directly to the printer using a simple cable. Then, using a chrome extension of “G-code Sender”, you can connect to the printer and send information directly to it. While this approach is quite simple, one of the major drawbacks is that if the computer goes into standby mode, the printing process will stop and potentially ruin the project. For this reason, it is generally recommended to use a desktop computer when transferring the G-code (Dwamena, n.d.-b).

#### *Wi-Fi Connectivity:*

A growing method of transferring G-code to a 3D printer is over a Wi-Fi connection. If the motherboard being used for the printer has Wi-Fi enabled, the user will be able to send their G-code files to their motherboard wirelessly. However, the board still requires a small SD card on board to store the required software to read the G-code and execute the commands, but the overall benefit is wireless printing. Alternatively, there are various software packages that you can implement, such as AstroBox, OctoPrint, or Repetier-Host (Dwamena, n.d.-b). These software packages can then run on a Raspberry Pi, a small single-board computer. The advantage of using a program like OctoPrint and a Raspberry Pi, is you can send G-code to multiple printers at the same time (*Why Do 3D Printers Still Use Storage Devices to Import G-Code?*, n.d.).

### 2.3.5 Calibrating Printer Firmware

Firmware is a special type of computer software that supplies low-level control for a device's hardware. Essentially, firmware is the link between the software and hardware. When it comes to 3D printing, firmware is needed to allow the user to interface with G-code outside of a strict printing protocol (like homing functions and such). The specific firmware that is used is often dependent on the type of motherboard being used (*The Best 3D Printer Firmware of 2022*, 2022).

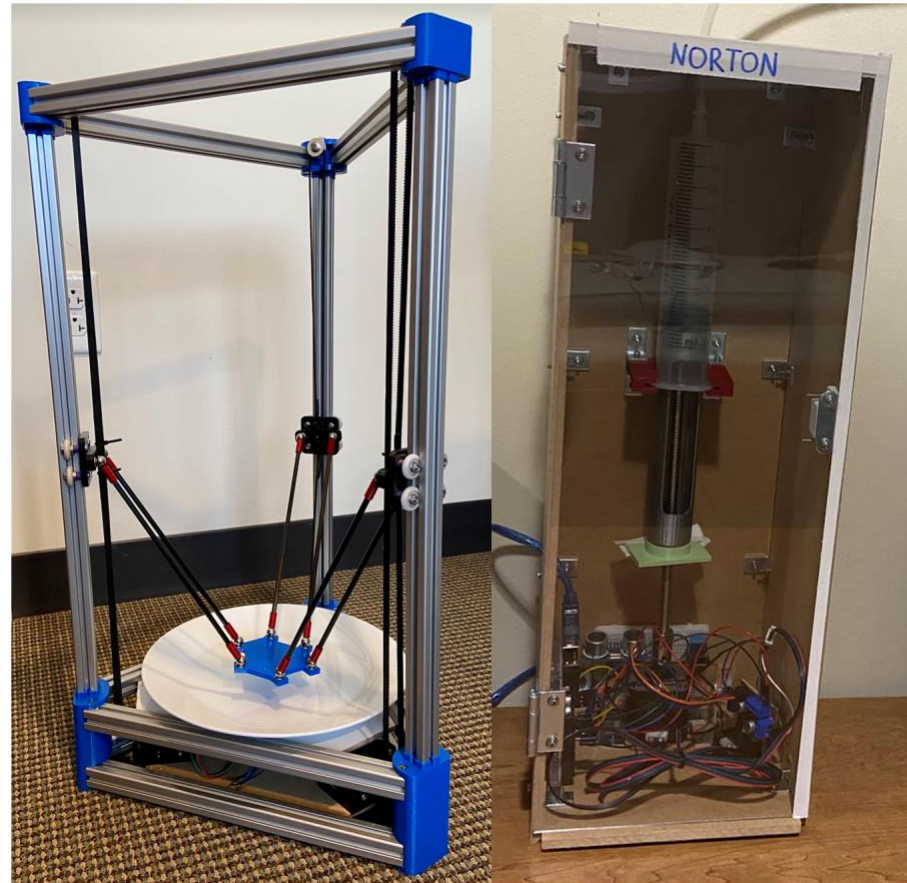
While there are already several printer measurements that go into the slicer program, the firmware must relay user-defined parameters about the printer. Some examples of these parameters are listed here:

- *“Number of extruders – How many extruders does the 3D printer have?”*

- *Heated bed – Is there a heated bed?*
- *Location of limit switches – Are the limit switches at the minimum or maximum of their respective linear guides?*
- *Z probe – Is there a Z-probe? If not, then how far away is the extruder from the build plate?*
- *Stepper motor rotation to linear motion – For each axis, how far does the carriage move per rotation of the stepper motor?*
- *Build Volume – What is the maximum travel for each axis?*
- *Direction – Does clockwise or counterclockwise rotation of each stepper motor result in positive movement?*
- *Filament extrusion – How much filament is extruded per rotation of the extrusion drive stepper?*
- *Speed – What is the maximum speed each motor is capable of?” (Florian, n.d.)*

## 2.4 Our Current 3D Food Printer

Our project will aim to implement an intuitive and “easy-to-use” user interface for a 3DFP that was designed by a student the year prior. The 3DFP we will work with is a Delta printer with an external Extruder system. The below figure (Figure 12) depicts the two systems that this project’s 3DFP has. This section summarizes the work done by the previous student to create such 3DFP (Toplyn, 2021a, 2021b, 2022).



*Figure 12 – Project’s 3DFP*



As stated in previous sections, having the extruder mounted to the effector plate is the most common in delta printers. However, due to how a 3DFP operates, with heavier material (in comparison to plastics), it is detrimental to have the syringe with the material mounted to the effector plate. The syringe would introduce too much weight to the effector plate and therefore increase the likelihood of the effector plate disconnecting, resulting in a failed print (let alone a broken machine). The external extruder uses a stepper motor<sup>2</sup> to rotate a threaded rod such that a platform drives a syringe plunger up into the syringe, extruding the material through a tube and to the printer's nozzle (attached to the effector plate). Figure 13 shows the overall system the extruder uses to extruder material, further details may be found in the student's previous reports (Toplyn, 2021b).

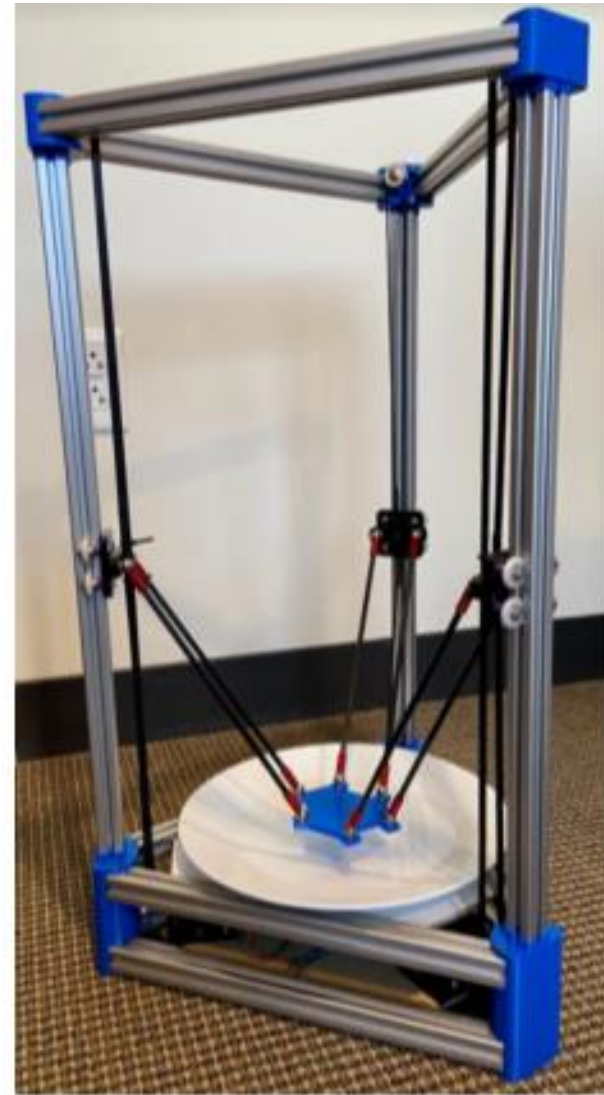


*Figure 13 – Our 3DFP External Extruder System*

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<sup>2</sup> We will be defining a stepper motor as a motor that divides a full 360 rotation into smaller increments that we will call “steps.”

The extruder system has a tube that brings the material to the effector plate of the 3DFP. The 3DFP is a linear delta-style printer that uses three vertical axes and three carriages to connect the arms to the effector plate. The carriages consist of three distinct parts, the carriage itself (or the component that the guide wheels are attached to), the magnetic diagonal rod/arm mounting plate, and the belt tensioner. The frame of the 3DFP is comprised of 3D printed parts to hold the printer in its triangular shape as well as offer a mounting location for the belt mounting. On the top connectors, there is a guide pulley that allows the belt to wrap back to the carriage and make a complete loop, such that the carriage may traverse the entire length of the vertical linear rail (or, Z-axis). The 3DFP's mechanical and structural components were designed and fabricated by a student in a previous project and described in greater detail in their reports (Toplyn, 2021a, 2022). Please refer to the following figure (Figure 14 – Our 3DFP Structural and Mechanical Components) for a visual representation of these components.



*Figure 14 – Our 3DFP Structural and Mechanical Components*

## 3.0 Methodology

To progress forward we needed to outline our project management, select a firmware as well as map out our documentation process. We determined that an iterative approach toward meetings and timelines proved to be the most productive for this project. We also, outline the decision process for selecting a firmware as well as outlining our documentation processes.

### 3.1 Project Management

We decided to use an agile software development methodology called Scrum to organize our workflow. The Scrum methodology uses iterative and incremental processes, allowing for teams to work together closely to solve a complex problem. Each iteration is called a Sprint which is a “short, time-boxed period when a Scrum team works to complete a set amount of work” ([Atlassian, n.d.-a](#)).

The Scrum methodology utilizes three “artifacts” which are set up by the team. These artifacts are revisited and changed over time as the project progresses. The three Scrum artifacts consist of a Product Backlog, Sprint Backlog, and Sprint Goal. These terms are defined below ([Atlassian, n.d.-b](#)):

1. Product Backlog: primary list of work that needs to be done

2. Sprint Backlog: list of items that need to be implemented and tested during the current sprint
3. Sprint Goal: end-product that should be implemented by the end of the sprint

Our sprints spanned a one-week timeline. At the start of each week, we created our Sprint Backlog based on comments we received from our advisors on our work from the previous week. We turned the feedback into action items that were either added to the Product Backlog or the upcoming Sprint Backlog. During this time, we also created our sprint goal based on the Sprint Backlog. This process is called organizing the backlog and sprint planning.

Once we created or updated the Product Backlog and Sprint Backlog, the team started the Sprint. Every day during the sprint, the team held 10-minute Scrums. Scrums (also called stand-ups) are “super-short meetings” whose goal is “for everyone on the team to be on the same page” ([Atlassian, n.d.-b](#)). We went over any progress we had made on tasks, any issues we had faced, and the plan for the current meeting.

Once the Sprint ended, the team held an event where we combined the Sprint Review and Sprint Retrospective. The Sprint Review is used to showcase the progress that has been made during the Sprint. The Sprint Retrospective is when the team came together to review the Sprint and “discuss what worked and what didn’t work” (Atlassian, n.d.-b). Once we completed this event, we repeated this process by updating the Sprint Backlog. Figure 15 shows the cyclical workflow that we implemented to manage this project.



Figure 15 – Scrum Methodology Workflow

We used a project management tool called Trello to implement our Scrum methodology. Trello was our best option since it is an easy-to-use, lightweight version of JIRA. JIRA is the most popular agile and software development project management tool used in professional workplaces. Trello gave us the ability to create, edit, assign, and complete tasks each sprint. Figure 16 shows our Trello board for this project and our weekly task breakdown. Our Sprint tasks were also easily imported into a calendar on Trello as shown in Figure 17.

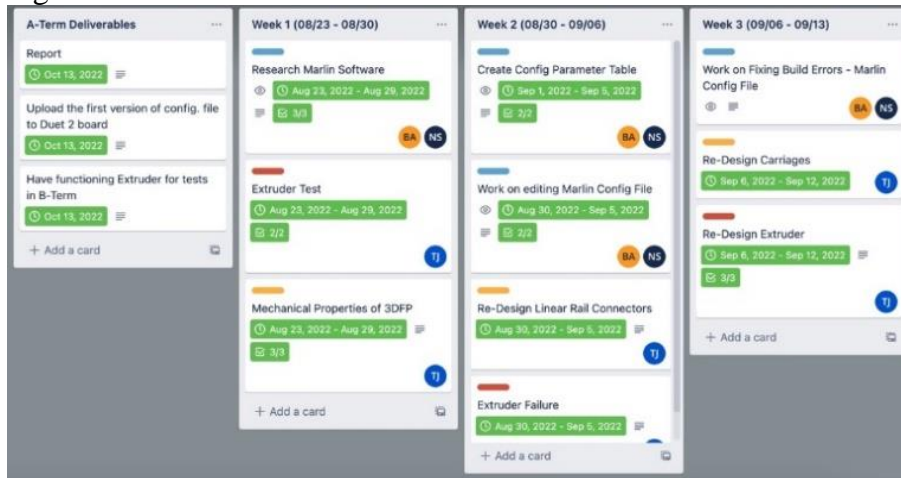


Figure 16 – Trello Board (Weeks 2 through Week 6)

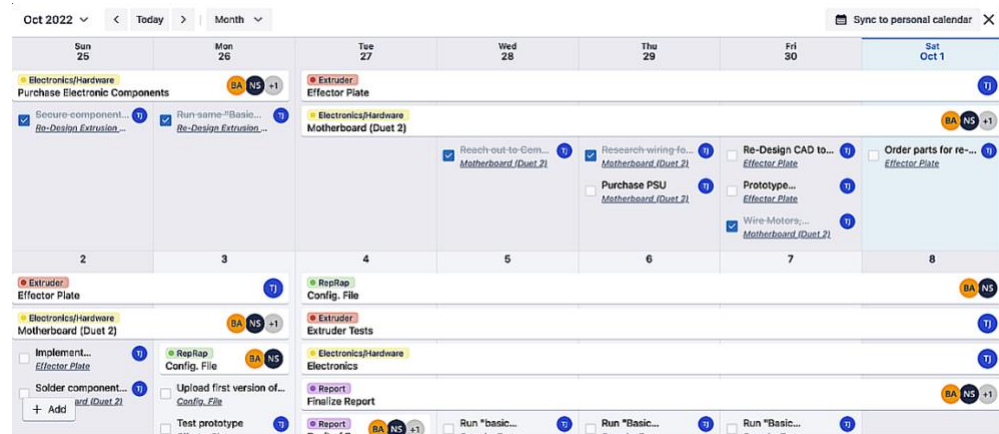


Figure 17 - Trello Calendar (Week 6)

### 3.2 Firmware

A critical consideration was the selection of firmware to implement on our printer. Firmware provides the user the ability to mechanically control the components of the printer, as well as acts as a bridge between the software and hardware components.

There were two reputable and well-documented firmware options for us to consider: Marlin and RepRapFirmware. Marlin is "one of the most widely known and commonly used 3D printer firmware options" (*The Best 3D Printer Firmware of 2022*, 2022). Marlin is an open-source program compatible with most boards. Our second choice, RepRapFirmware, is also open source; however, it is most notable for its web-based configuration and control. In this case, Marlin became less user-friendly as users need to set-up an environment, whereas RepRapFirmware provides one with its web-based control tool. Overall, these features became the leading factor in choosing RepRapFirmware as our firmware.

### 3.3 Video Documentation

“Short video clips are invaluable for illustrating procedures, findings, and phenomena... If a picture is worth a thousand words, then video is worth a thousand pictures” (*Video Data and Documentation Will Improve Psychological Science*, n.d.). For that reason, we chose to document the components of our research on our YouTube channel. Two main components needed to be documented: the processing of setting up the printer and the process of using the printer. These processes are critical to understand to be able to successfully utilize the printer. Our process of creating and editing these videos are extensively discussed in Section 4.8 YouTube Tutorials.

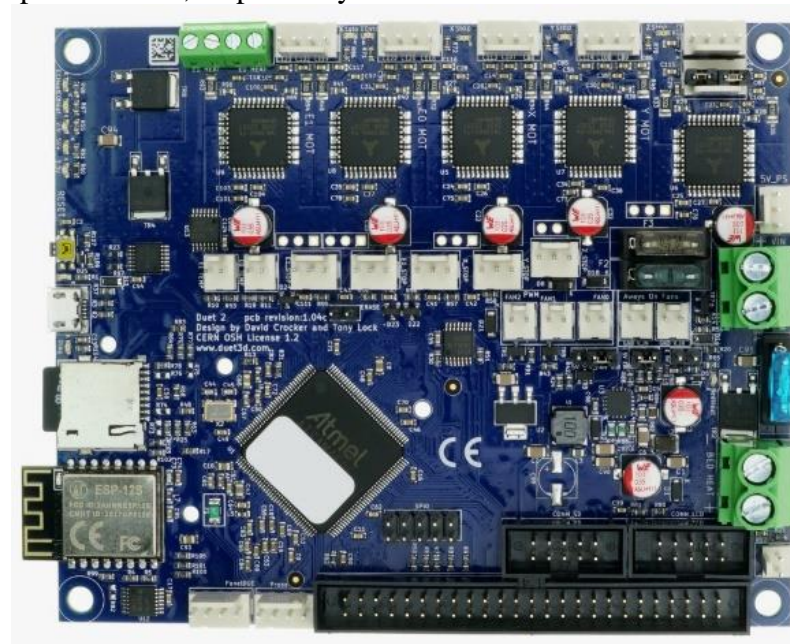
## 4.0 Results and Findings

This section presents a detailed discussion of the outcomes and discoveries resulting from our adoption of RepRapFirmware as the firmware of choice for our printer. Subsections 4.1 to 4.3 are a direct result of this decision. Subsequent subsections, from 4.4 to 4.6 discuss further findings and results.

### 4.1 Motherboard Selection

A 3D printer's motherboard<sup>3</sup> is the heart of the printer as it is responsible for parsing G-code and controlling the motions of the printer. There are many different motherboards on the market that support different firmware. Due to our choice to use RepRapFirmware, the compatible motherboards then became constrained to ones that support only this firmware. As a result of our collaboration with Mr. Aygul, we found that the Duet 2 Ethernet best supported our electrical needs and was well documented. Figure 18 depicts the Duet 2 Ethernet board. The purchase of the Duet motherboard was also heavily influenced by our experiences with our previous motherboard, a controller kit with an Arduino board and a Longrunner GRBL CNC Shield. The previous motherboard ran Marlin in Arduino IDE, another common 3D printer firmware. Despite the extensive availability of documentation on Marlin and its capabilities, we encountered difficulties comprehending the technical terminology and effectively integrating the numerous features of Marlin into our 3DFP. Thus, we determined it to be paramount and one of our leading objectives to make the documentation around the motherboard and firmware implementation simple and easy to follow. Further specifications of the Duet 2 Ethernet and Longrunner board can

be seen in Appendix A: Duet 2 Ethernet Motherboard Specifications and Appendix B: Longrunner Motherboard Specifications, respectively.



*Figure 18 - Duet 2 Ethernet Board Purchased  
(Duet 2 WiFi and Ethernet Hardware Overview, n.d.)*

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<sup>3</sup> A motherboard is also sometimes referred to as the controller board or simply “the board.”

## 4.2 Duet Web Control (DWC)

Through our purchase of the Duet3D Duet 2 Ethernet motherboard, we also acquired the onboard user interface, Duet Web Control. DWC comes with an extensive set of features that allow us to use our own personal devices to communicate with the printer. Various features are customizable, which we highlight and discuss later in this report.

DWC provides a straightforward user interface, allowing the user to control and monitor different elements of their printer from one central location. Within DWC's main dashboard, there is helpful information about the machine, including the exact coordinates of the tool head, the position of the extruder, as well as speed, heating, and sensor(s) information. From the dashboard, the user can control the position of the printer head and control the extrusion of material(s) if desired. Additionally, the user can monitor the console's output of the machine, watching for any errors that might arise during the operation of the machine. From the console, used to aid in debugging, the user can also send single lines of G-code directly to the printer. Through the addition of the "Height Map" plugin, a user may easily monitor any z-coordinate offsets of the build surface, which yields itself towards leveling the print bed. Through the use of a z-probe installed on the printer, this widget would visually display a helpful mesh map.

Prior to beginning a print job, DWC supports a 3D G-code viewer. This plugin allows you to upload a print job in the form of a .gcode file and visually see the toolpath of the machine. This feature serves as a way to virtually "dry print" without using calling any of the mechanical components of the machine itself, helping to detect errors before the print begins. Once ready to print with the machine, DWC allows the user to track the status of any print job. As a print job is in progress, the Status menu (nested with the Job dropdown) provides any information

regarding the current print job, such as duration, a layer chart, filament usage, layer height, etc.

Additionally, DWC allows users to edit key files on the SD card within the motherboard without needing to eject the card from the board itself. This feature greatly streamlines the process of editing commonly called files. As discussed further in Section 4.7.2 Added Macro Files, DWC provides a user interface to write additional G-code scripts, which can be used to add additional functionality to the printer. These scripts are called Macros and proved to be very helpful to our project. DWC provides a streamlined UI that facilitates easy editing of key files used for testing purposes, specifically the config.g file.

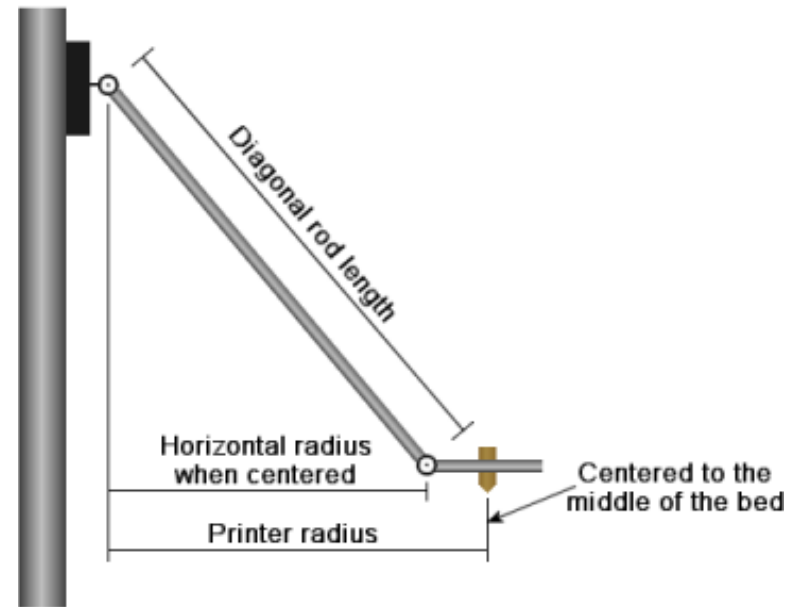
## 4.3 Configuration File

The configuration file describes our printer to the firmware by storing our printer's most important measurements. When we execute any tasks (homing, printing, leveling, etc.), we rely on this configuration file to determine the bounds of each of these tasks. To create config.g (the name of the configuration file), we used the RepRap Configuration Tool — a user interface to generate the configuration file. This tool became available for our team to use because we chose to use the RepRapFirmware. This web-based tool allowed users to choose printer type, specify printer measurements, define electrical pieces (i.e. endstops or motors), and state printer name and password specifications. Figure 19 defines some of the printer measurements that the RepRap Config Tool required to generate the configuration file. Appendix C: 3D Printer Measurement Photos shows some of the measurements we took to complete this configuration file.



We downloaded the .zip file that was generated from the RepRapConfig tool. This .zip file contains the config.g file and some other important G-code files such as homedelta.g, stop.g, bed.g, sleep.g, and more. We uploaded the configuration file to our SD card on our Duet2 board.

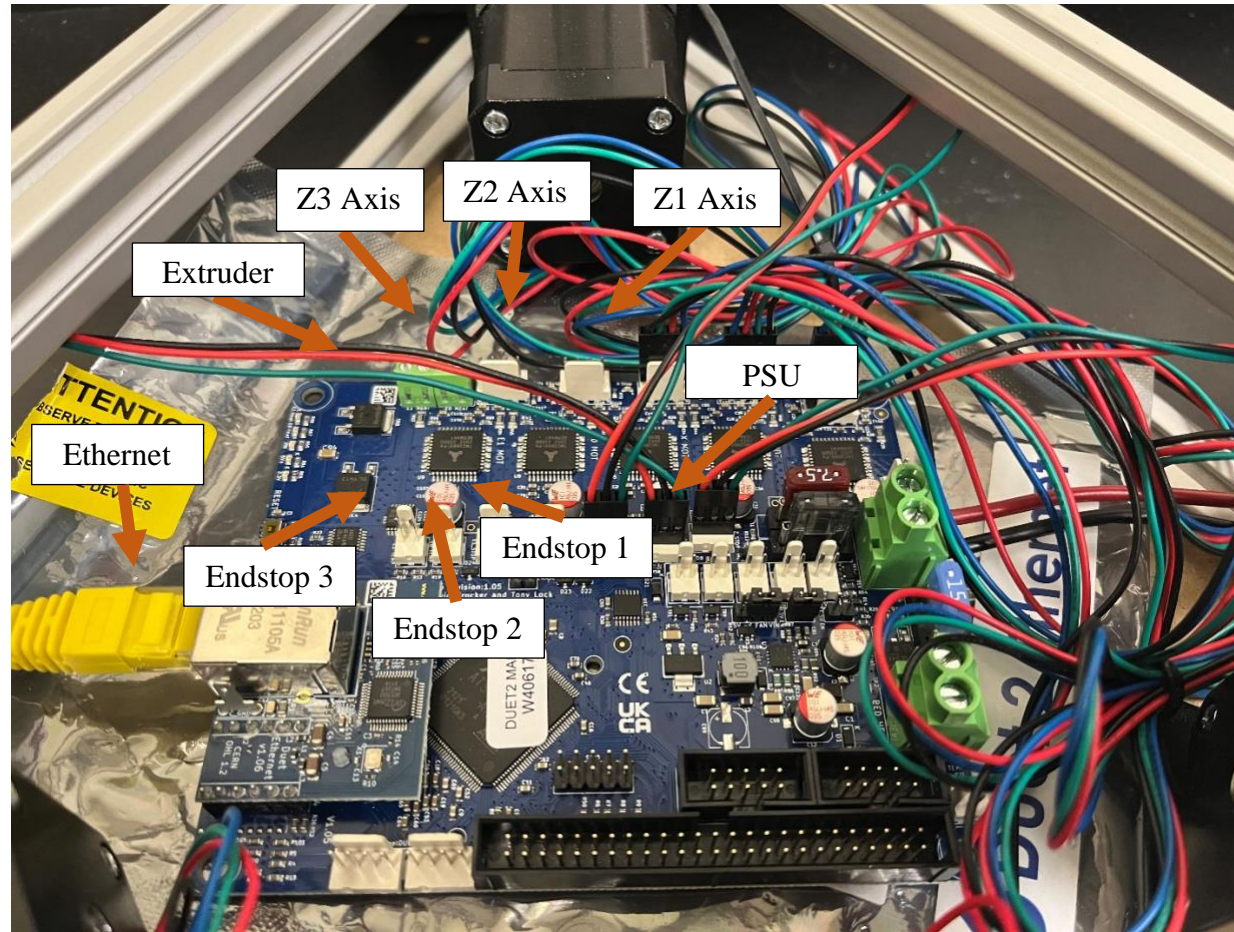
Once the configuration file was uploaded and produced no errors, we began performing some tests to ensure that the measurements we used as input were correct. For example, to test whether the configuration file stored the correct height of the printer, we moved the printer head down to the baseboard. From this test, we were able to compare the height we had used as input to the height that the printer thought it was (this measurement is displayed on the DWC dashboard). We continued running small tests and tweaking some of the measurements in the configuration file until we were satisfied with the configuration file.



*Figure 19 - Delta Configuration Measurements Guide*



As previously stated, the board surpasses our needs, thus, we only utilized the following electrical connections: power delivery, Drives 1-3 (calling Drive 4 only for extruder testing), and the Xstop, Ystop, and Zstop. Figure 21 displays our wiring for the motherboard.

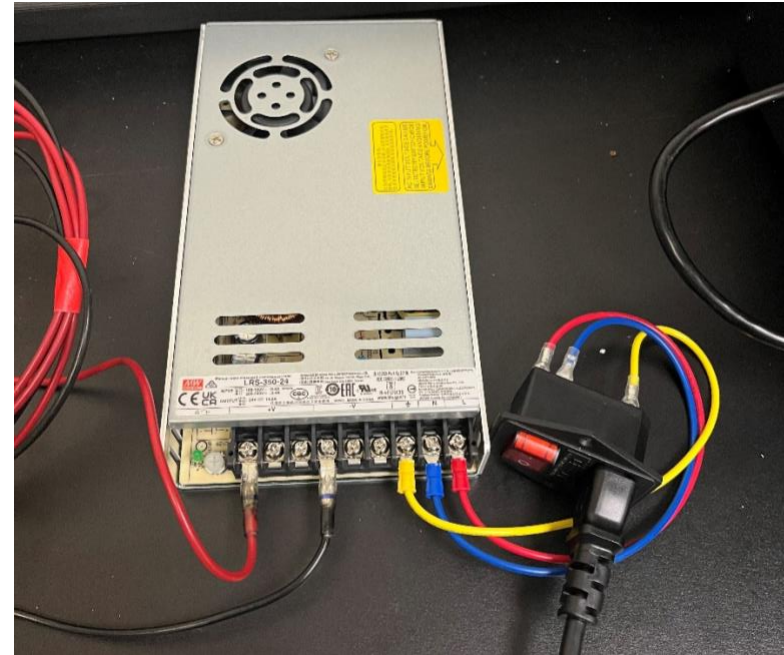


*Figure 21 - Current Wiring of Motherboard*

#### 4.4.1 PSU choice

As stated above, we utilized the power module on the motherboard. Along with the electrical wiring documentation, Duet3D provided recommendations for Power Supply Unit(s) (PSU) based on the desired mechanical components. We determined that a 24V PSU would be ample enough to supply power to three stepper motors, one stepper motor for the extruder, as well as three endstops.

We purchased a “Meanwell 24V 350W” single output switchable power supply. This PSU can deliver up to 24 volts and 350 watts of power at any given time. While our components did not call for this much power, we did not want to limit any future expansive possibilities by creating a power bottleneck. The purchased PSU can be seen in Figure 22.



*Figure 22 - Power Supply Purchased with Wiring*

#### 4.4.2 Router

As stated previously, we purchased an ethernet equipped motherboard. We determined that an ethernet connection would be the most stable internet connection. A stable internet

connection was crucial for DWC to operate and communicate with the 3DFP properly.

We purchased the “TP-Link AC 1750 Dual Band Wireless Router,” as pictured in Figure 23. We consulted with another student on campus to confirm that this router could interface with our motherboard and WPI’s ethernet protocols. In a subsequent consultation, we confirmed with WPI IT that this ethernet would be able to interface with the ports available to us within our laboratory. Thus, due to the compatibility of this router, we have loaned one from the Computer Science Department to facilitate our ethernet connections.



*Figure 23 - TP-Link Router as in Lab*

#### 4.4.3 Motors

The printer's axis movement are powered by one NEMA (The National Electrical Manufacturers Association) 17 Stepper Motor, respectively. Stepper motors are a class of rotary motors that utilize sets of coils (often referred to as phases) that induce a magnetic field, and thus rotates the center shaft. Once each phase has been energized in sequence, the shaft will have rotated "one step." In the context of this paper, we refer to this cycle of phases as "a step."

We opted for these motors due to their relatively low power draw to torque output. As stated previously, our PSU is able to deliver 24V, so we had to ensure that our motor's power consumption would not exceed this value. While NEMA 17 motors are not one of the highest torque producing motors, they are sufficient to move our gantries while remaining under the voltage threshold.

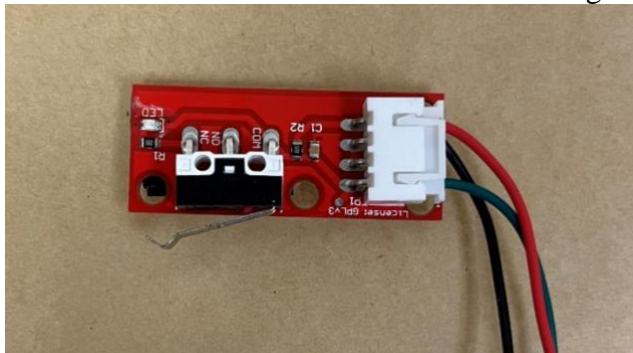
Another consideration for the motors were the size and mounting locations. The electrical compartment, or the area where the motors and motherboard are stored, is limited in height. Any motors we chose had to be under 2.5 inches. There were two NEMA stepper motor sizes that would fit within this clearance – NEMA 17 and NEMA 23. The NEMA 17 motors have a height of 1.7 inches and the NEMA 23 motors have a height of 2.3 inches. While the NEMA 23 motors could fit the clearance, the wires would be at a harsh 90-degree angle, which could result in failure in the near future. Thus, we opted for the NEMA 17 motor size.

Another consideration for the motor selection was the depth of the motor itself. NEMA stepper motors come, most commonly, in two different depths: "normal" or "pancake." Both depths offer the same holding torque, so regardless of the depth chosen, there is no loss in mechanical output. While the pancake motor

would have been an optimal and ideal choice for this project, as to provide more space for the motherboard and any expansions later on, the "normal" depth motors were the only ones available for us to purchase in the timeline of our project. Thus, the 3DFP uses three NEMA 17 stepper motors (of normal depth) to move the vertical axes.

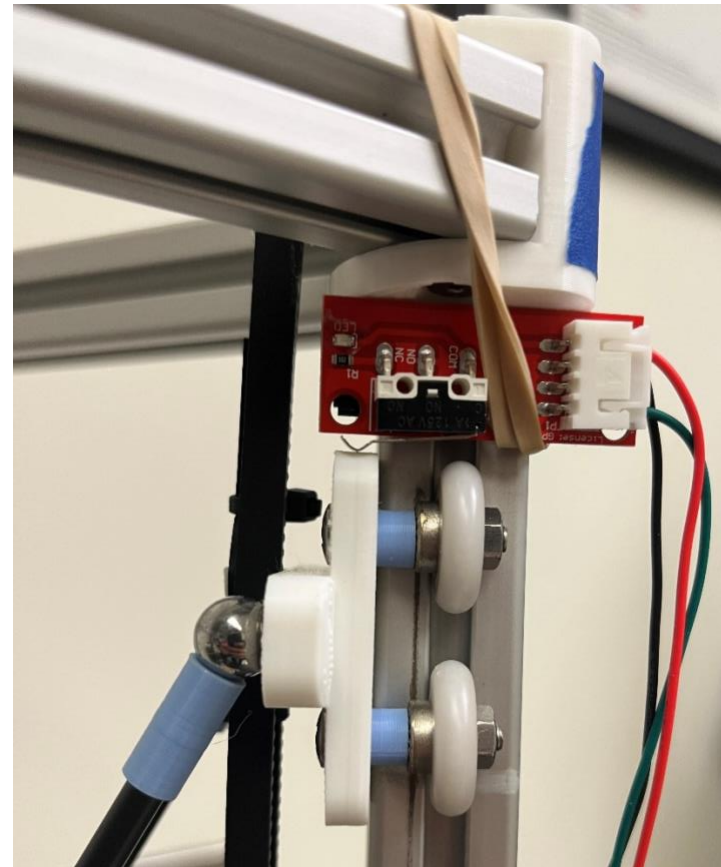
#### 4.4.4 Endstops

This printer utilizes a mechanical component called an “endstop.” In its most basic function, an endstop informs the machine of its upper or lower most bounds. Endstops, commonly use a mechanical switch, an optical sensor, or probe to convert an analog input to a digital output. The switch, when triggered by a component of the printer, in our case the gantry, outputs a “true” or “false” statement. This switch and respective “states” inform the machine that for the respective axis, the machine has reached the maximum or minimum distance of travel. The mechanical switch we chose is seen in Figure 24.



*Figure 24 - Mechanical Switch Endstop*

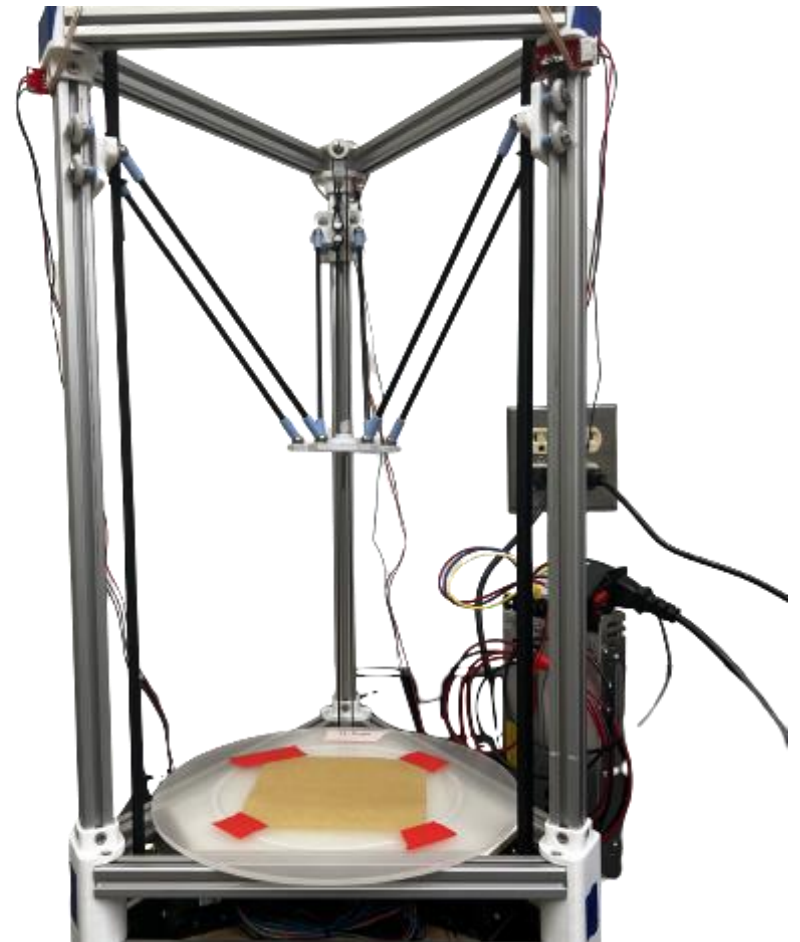
For our machine, we used three endstops mounted to the topmost part of the three vertical rails on the 3DFP. These endstops marked the maximum vertical distance any one gantry could move along the respective axis. We used a mechanical switch system for the endstops, meaning a small switch would be depressed by the gantry and trigger a switch in state (i.e., “true” to “false”). The depression of the mechanical switch may be seen in Figure 25.



*Figure 25 - Depressed End Stop*

#### 4.5 3DFP

In order to implement and fully utilize the electrical components listed above, the structural components of the 3DFP needed to be redesigned. The following subsections outline the design process for each structural component and their revisions so that the machine can facilitate the basic functions of a 3D printer. Figure 26 below depicts the implementation of these changes.



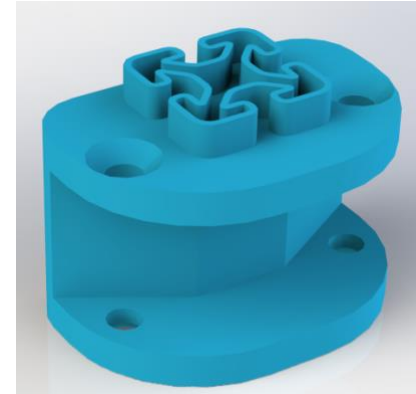
*Figure 26 - Current 3DFP with Improvements Implemented*



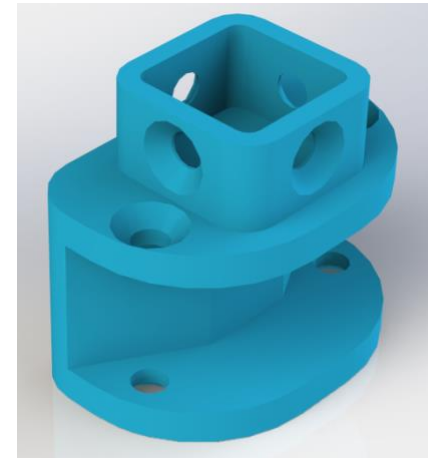
#### 4.5.1 Linear Rail Connector Improvements

The linear rail connectors in the design maintain the linear rails' angle, fasten the vertical rails to the bottom and upper triangle, and provide stability as the carriages move along Z-axes. The previous design used a press-fit collar to hold the vertical rails and a machine screw with a square nut in the channel of the linear rail to fasten the connector to the rail. Figure 27 provides a visual of these components.

While this design effectively angled the rails, it did not hold the vertical rails in place well and often popped out of the press fit when the user moved the carriages. If the vertical rails were to dislodge during printing, the print would fail, and the printer itself could be significantly damaged. Therefore, we determined it paramount to improve upon this design. In our re-design, we chose to add a more secure way of fastening the vertical linear rails to the connector. We added a taller collar that uses 4 machine screws and 4 square nuts to hold the linear rail more securely. Figure 28 outlines these design changes.



*Figure 27 – Initial Linear Rail Connector Design*

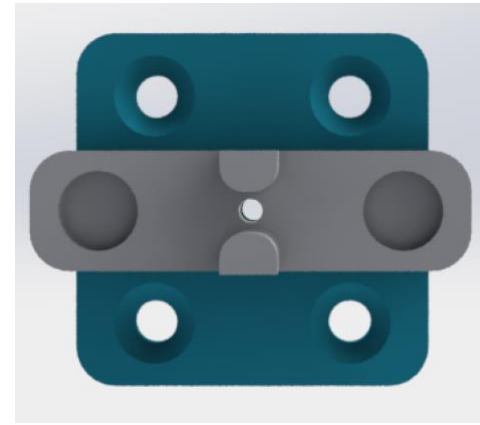


*Figure 28 - New Linear Rail Connector Design*

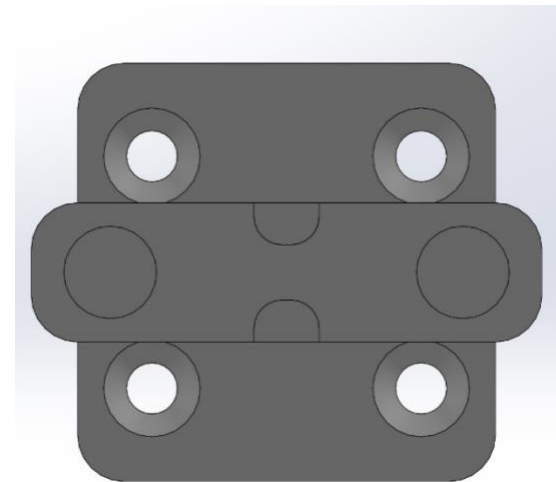
#### 4.5.2 Carriage Improvements

The carriage of this delta 3DFP has three primary purposes, facilitate vertical movement along the Z axis, connect the rods from the effector plate to the carriage to facilitate movement, and provide a means of connection and tension for the belts. The previous design utilized four shower door guide wheels to allow the carriage to move along the linear rail with reduced friction. The carriage had a bar with magnets that was fastened to the carriage using a bolt and nut; these magnets served as the connection point for the rods/arms of the printer. The carriage also had two rounded pegs to wrap the belt around that, when zip-tied, served as a belt tensioner, as seen in Figure 29.

We found that the bar which holds the printer's arms had too many degrees of freedom to be effective. This was primarily due to the fact that the bar containing the magnetic joints was secured to the back plate with only one bolt, allowing the entire bar to rotate about that point. This resulted in an unstable effector plate and imprecise arm locations. Thus, for our redesign, we combined this bar and back plate into one piece. We did not feel the need to redesign the ways that the wheels/guides mount to the back plate nor the belt tensioning of the previous design. When we held the bar stationary those components were functioning well. Please refer to Figure 30 for a visual depiction of the new design.



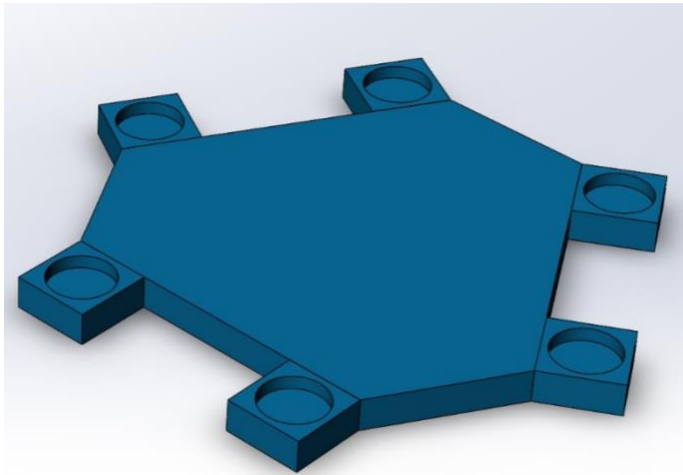
*Figure 29 – Initial Carriage Design*



*Figure 30 – Current Carriage Design*

### 4.5.3 Effector Plate Improvements

Another area in which needed improvements was the effector plate. The original effector plate did not have a way to interface with any nozzle nor did it connect to the extruder. This proved to be a problem as it meant that we were unable to perform any printing. If the extruder doesn't interface with the effector plate, there is no way to get the material from the extruder to the tool head/ nozzle such that the machine can perform a print. Figure 31 depicts the current effector plate.



*Figure 31 – Initial Effector Plate Design*

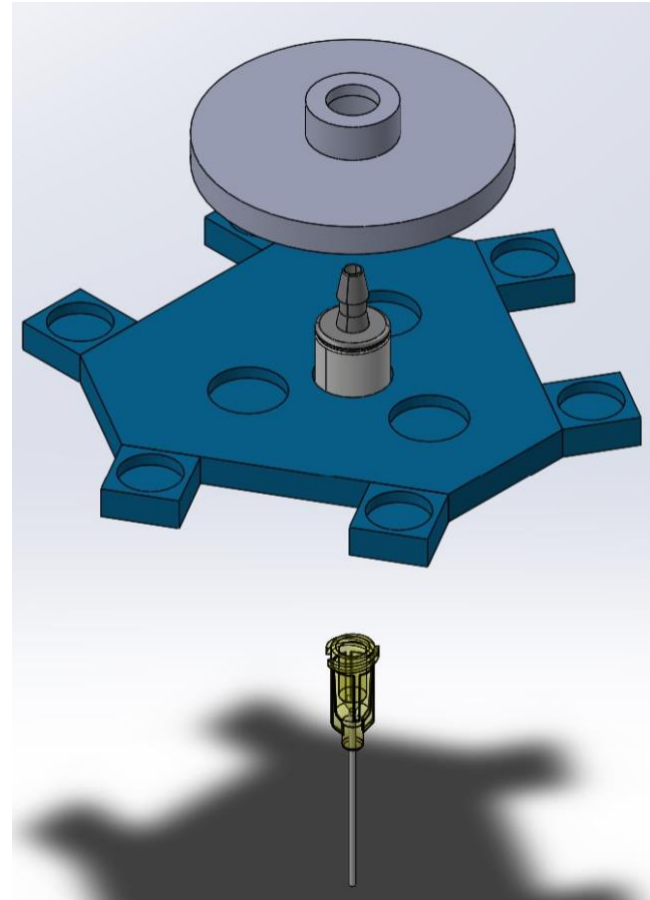
In our re-design, we deemed it necessary to have an efficient way of changing the nozzle as well as connecting the extruder to the effector plate was essential. Changing nozzles is a critical feature to have as different viscosities of materials require a larger or smaller opening to create precise prints. The more viscous a material, the larger the nozzle needs to be, whereas the less viscous a material, the smaller the nozzle should be to ensure accurate printing. Therefore, we needed to create a

simple way of changing the nozzle and an easy way to connect the effector plate to the extruder system. Currently, the only way to connect to the extruder system is via a medical grade 3mm wide tube. It is paramount that this connection is airtight as to ensure that material extruded through the tube travels through the tube and to the nozzle, rather than oozing out before the nozzle.

Therefore, our redesign prioritized the above two criteria. To make nozzle changes quick and efficient, we had to utilize syringe connector types. The nozzle types we have in our laboratory are commonly referred to as “blunt tip needles.” These types of syringe tips have a technology that allows them to interface with a plethora of different syringe sizes, the connector is called a “Luer Lock.” Luer locks are proprietary types of connection points that allow syringes to have different needle tips, connect to tubing, or even to other syringes. Utilizing this type of connector allowed us to join the tubing to the nozzle.

Ultimately, we designed around the use of a male luer lock with a barbed tip. The barbed tip inserts into the tube from the extruder and has a female receptacle on the other end that interfaces with any luer lock blunt tip needle (or, our nozzles). The redesigned effector plate secures the luer lock and nozzle at the center of the plate. The barbed end is directed towards the top of the printer and can attach to the tubing from the extruder.

We found that we needed to secure the luer lock tightly, as when material comes through the tube from the extruder, it begins to pull the luer lock and nozzle out of the effector plate. We have implemented magnets into our design to secure the luer lock in place. The magnets make it easy to switch the nozzle and clean the tubing when necessary. Figure 32 depicts the new design of the effector plate.



*Figure 32 - Current Effector Plate Design*

## 4.6 Extruder

We tested the extruder by extruding materials with varying viscosities. We aimed to ensure that the extruder may print a wide variety of materials, primarily jelly and peanut butter. However, we found that the original extruder was unable to extrude jelly consistently. This failure to extrude jelly informed us that we wouldn't be able to print with more viscous materials. Therefore, hoping to avoid this limitation, we explored different re-designs of the extruder mechanism. The following subsections outline this process.

### 4.6.1 Mechanical Differences

The original extruder worked by a stepper motor rotating a threaded rod. Attached to this threaded rod was the syringe plunger (attached via a platform) that moved vertically as the rod spun. The syringe body itself was held stationary as the plunger moved upwards (extruding material) or downwards (pulling material back). We found that this system was not strong enough for food materials. The extruder was able to extrude material out of the syringe, through a tube, and to the nozzle attached to the effector plate in the printer. However, by having the threaded rod directly below the syringe plunger, the motor would receive back pressure from the syringe during the extrusion process. This backpressure proved to be too great for the motor, as it missed steps and resulted in uneven extrusion. Please refer to Figure 33 for a diagram of the original extruder design.

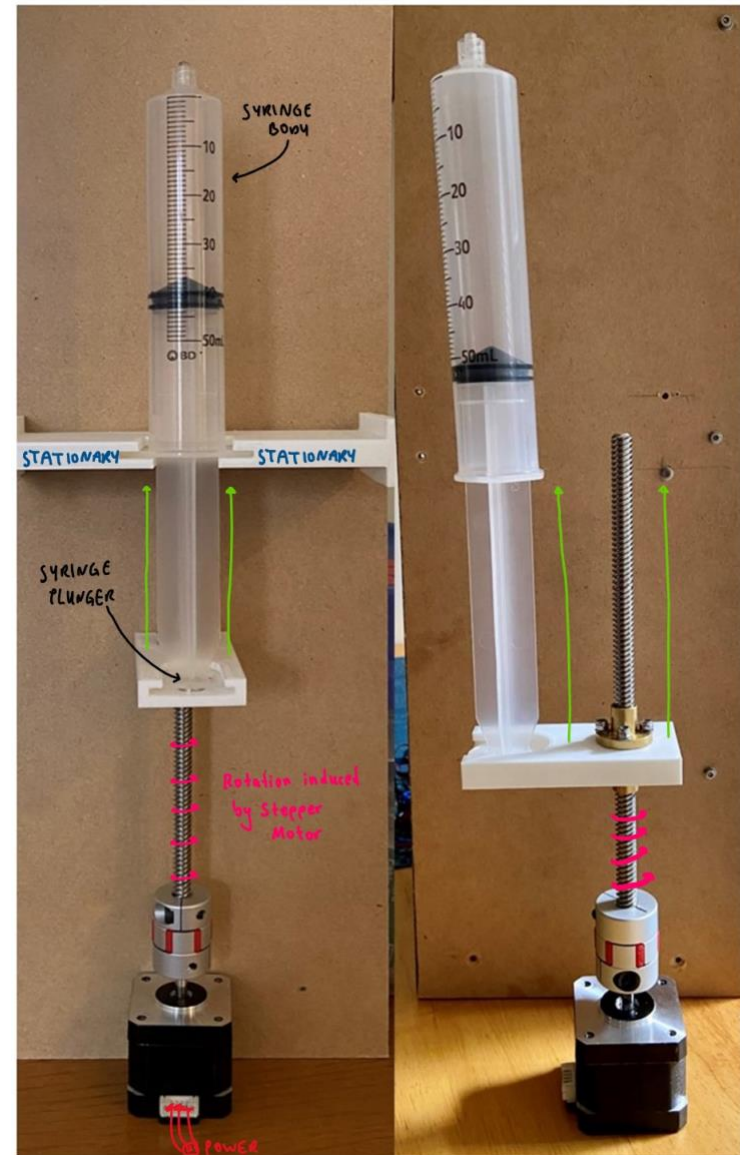


Figure 33 - Old Extruder Design

The new design utilized gravity instead of trying to work against it. Rather than trying to drive the syringe plunger upwards, this new design lowers the syringe body (and the material enclosed) down onto the plunger. The weight of the material, aided by gravity, reduced the amount of back pressure felt by the stepper motor. We also pivoted from a threaded rod design to a pulley-based system, one much like the systems present within the 3DFP.

This pulley-based system has three main components to facilitate movement. First, a stepper motor, that applied torque in small increments (called a step). Attached to this stepper motor is a pulley that acts in tandem with an idler pulley. This idler pulley is attached a set distance above the pulley attached to the stepper motor to create two endpoints for the timing belt. Third, there is a platform where the ends of the timing belt are attached.

This platform has two primary functions. First, attach to a set of linear rails such that guide wheels facilitated vertical movement with little frictional forces. Second, this platform acts as a tensioner for the timing belt. For timing belts to translate the torque from the stepper motor, there should be a significant amount of tension throughout the belt. This platform also has a cut-out for the syringe body, such that, as the platform traverses the linear rails, the syringe moves in tandem with the platform. The following figure, Figure 34, visually depicts this relationship.

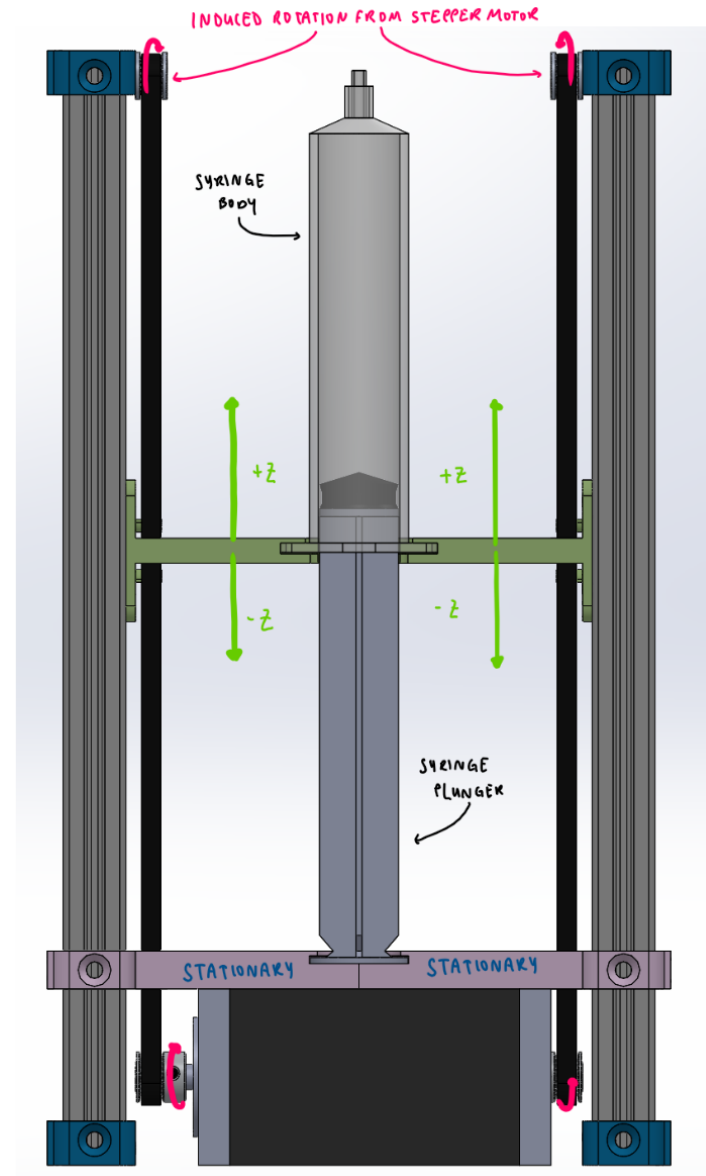


Figure 34 - New Extruder Mechanism

#### 4.6.2 Design of Extruder Structural Components

The new design called for the introduction of linear rails to facilitate the movement of the syringe platform (rather than a threaded rod). These linear rails serve two key purposes, first, as a guide to the syringe body platform movement, and secondly, as a mounting point for the stationary syringe plunger platform. Thus, it is paramount that these linear rails are secure and do not experience large amounts of vibration. The linear rails in this design are secured within the extruder box by flanged linear rail caps. Figure 35 depicts the linear rail cap model.

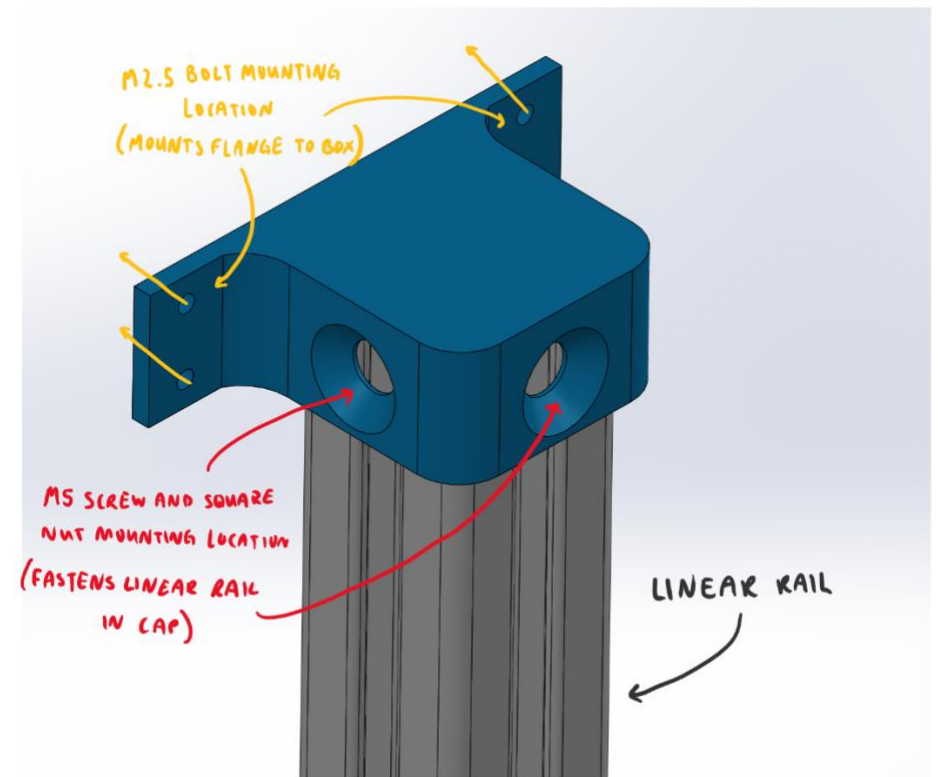


Figure 35 - Linear Rail Cap Design

These flanged caps allow the linear rod to be mounted to the walls of the extruder box without the hardware interfering with the pulley and belt. The cap also serves as a vibration dampener, transferring the vibrations produced by the stepper motor through the linear rails and to the walls of the extruder box, to then dissipate to the environment. The linear rail caps also serve as a mounting point for the idler pulleys that form the timing belt loop as outlined in the previous section. Please see Figure 36 for an example of this mounting point.

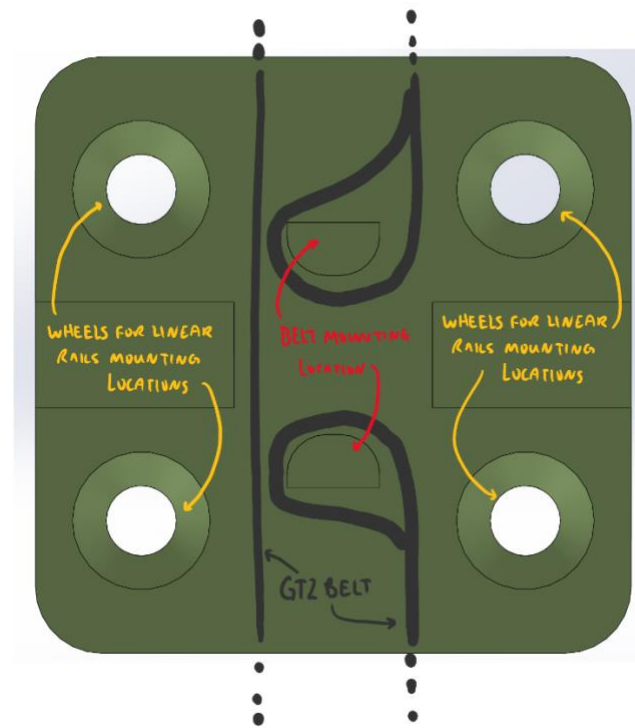


Figure 36 - Timing Belt and Linear Rail Guide Mounting Example



### 4.6.3 Syringe Platform Re-Design

For the syringe platform re-design, we needed to ensure that the body of the syringe could move vertically along a set of linear rails as well as be secured as to reduce wobble during the extruder movement.

The vertical movement, as seen on the 3DFP, uses a set of four wheels to move the platform up and down the rail. These wheels connect to the platform via screws and nuts. The platform then must also have a location for the belt to connect to. The belt, when attached to the platform and the pulleys at the top of the rail and the stepper motor allows the torque from the motor to move the belt in a counterclockwise or clockwise direction, which translates to the platform's positive or negative traversal of the z-axis. Please refer to Figure 37 for a depiction of these components.

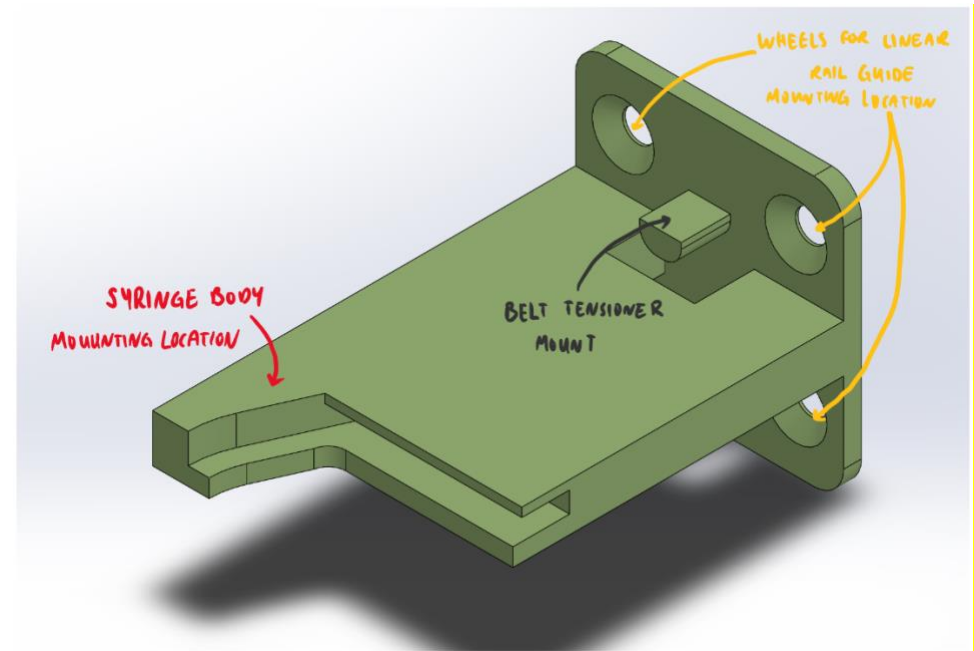
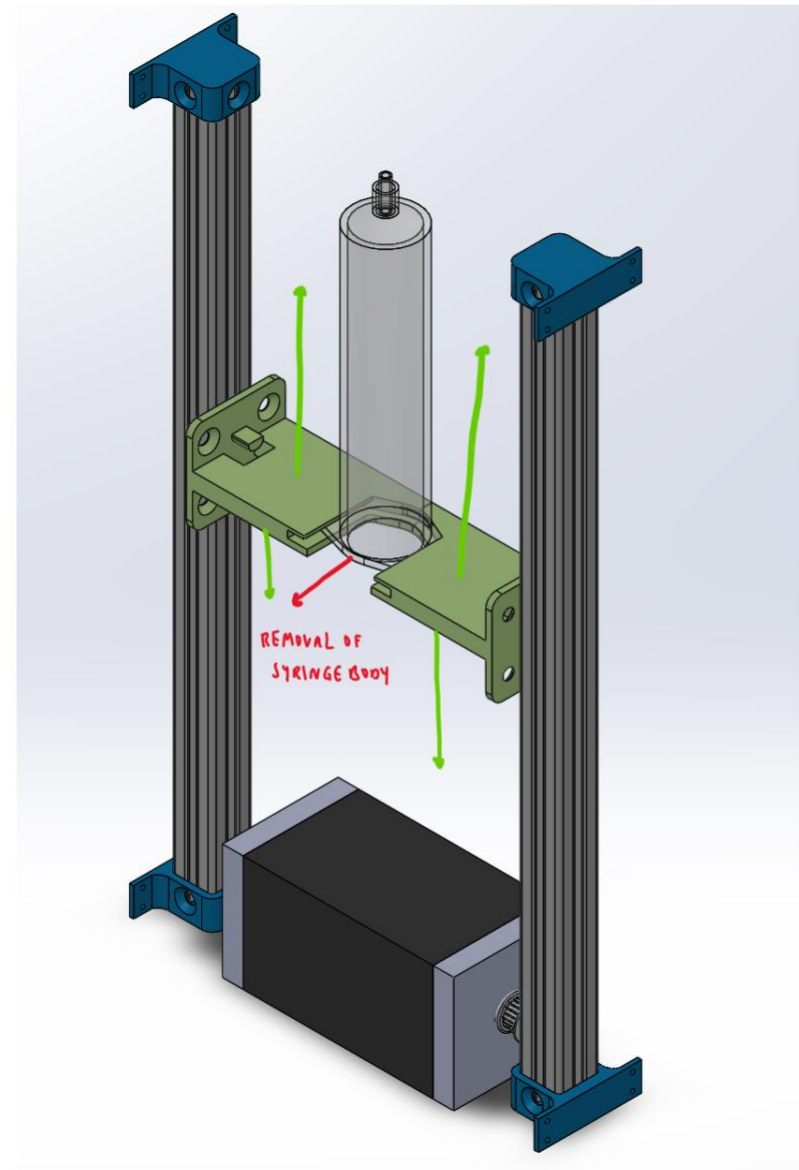


Figure 37 - Syringe Body Platform Re-Design

This design also needs to secure the syringe body. If the syringe wobbles during the extrusion process more forces are introduced which increases the likelihood of the extruder failing. For example, if the syringe body is wobbling during the extrusion process, more of the torque of the stepper motor will be

translated to the wobble, which, if these forces become too great, can dislodge the syringe from the system, resulting in complete extruder failure. Thus, this design incorporates a channel for the flange of the syringe to insert to. This channel serves two key purposes. First, it ensures the same alignment with the syringe plunger every time, it allows the vertical movement to be equally transferred to each side of the flange. By evenly distributing the forces felt during the extrusion process, we reduce the pockets wherein forces may grow exponentially, aggravated by vibrations. Please refer to Figure 38 for the relevant CAD model.



*Figure 38 - Syringe Body Re-Design*

#### 4.6.4 Plunger Platform Re-Design

The plunger platform must ensure that the plunger of the syringe remains stationary and upright during the entire extrusion process. Like the syringe body re-design, this platform will secure the linear rails. However, this mounting type will be a permanent one, rather than a flexible and movable one. The syringe plunger platform has a collar that goes around the linear rail, which has mounting locations for hardware that will secure the collar to the desired vertical position on the linear rail. Please see Figure 39 for an example of this collared design.

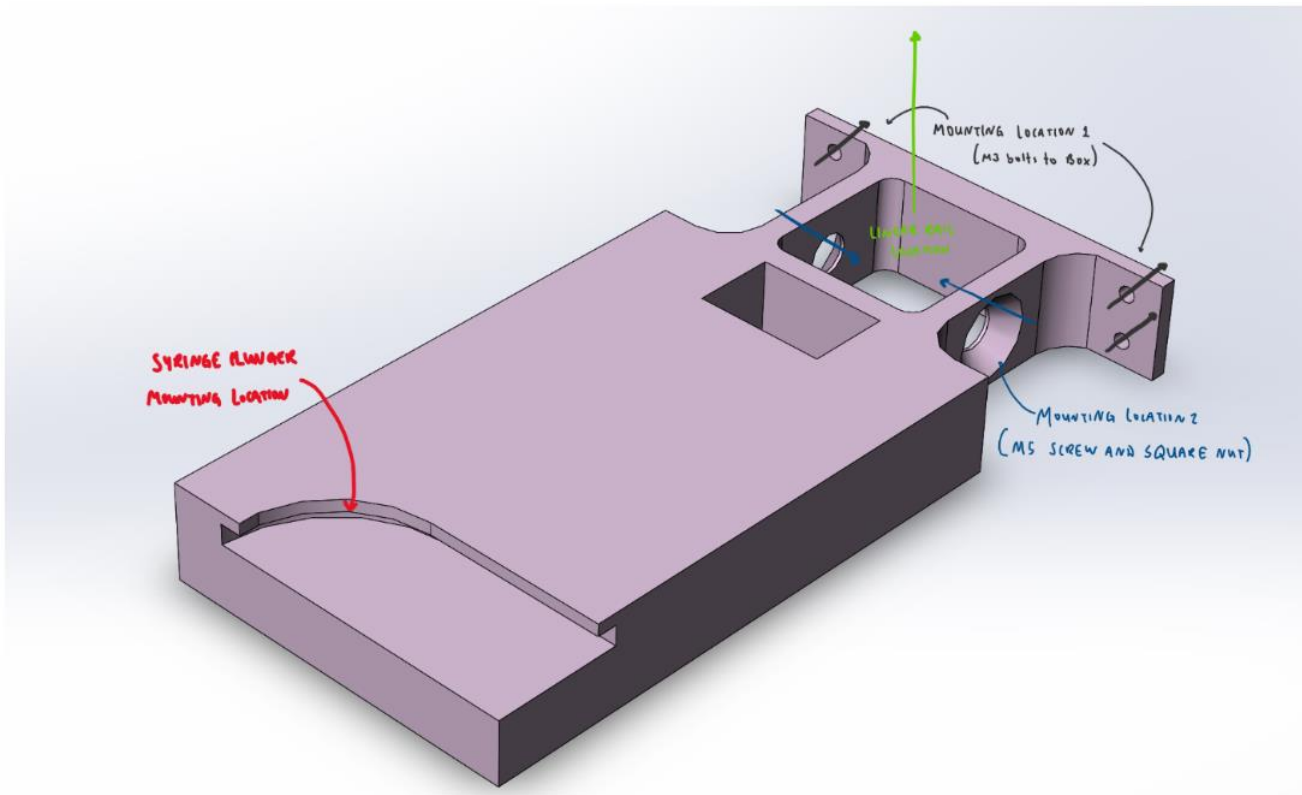


Figure 39 - Collared Syringe Plunger Platform Design

## 4.7 Investigating User Interface

There are several significant features offered by DWC that enhance both user experience and functionality. The following subsections elaborate on each of these features in more detail.

### 4.7.1 Customizable Features

The most advantageous feature we discovered was the capability to change the increments on the dashboard, allowing us to customize the amount the gantry moves in millimeters. Figure 40 shows the process of changing these increments.

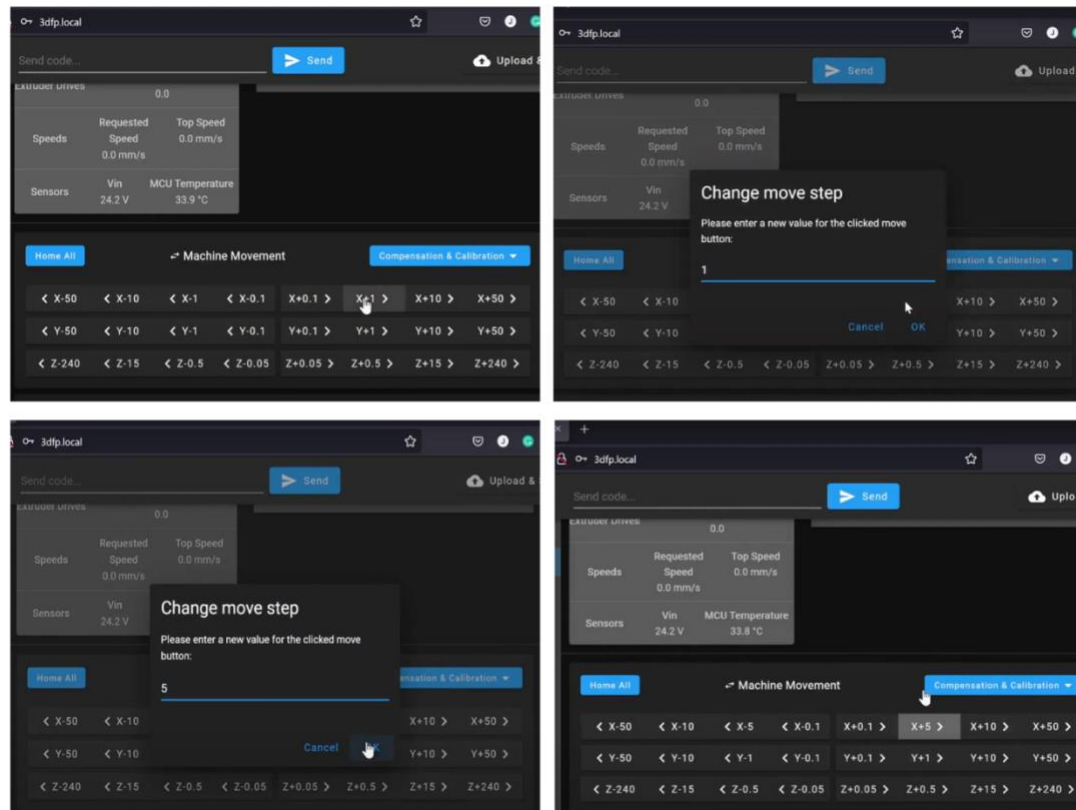
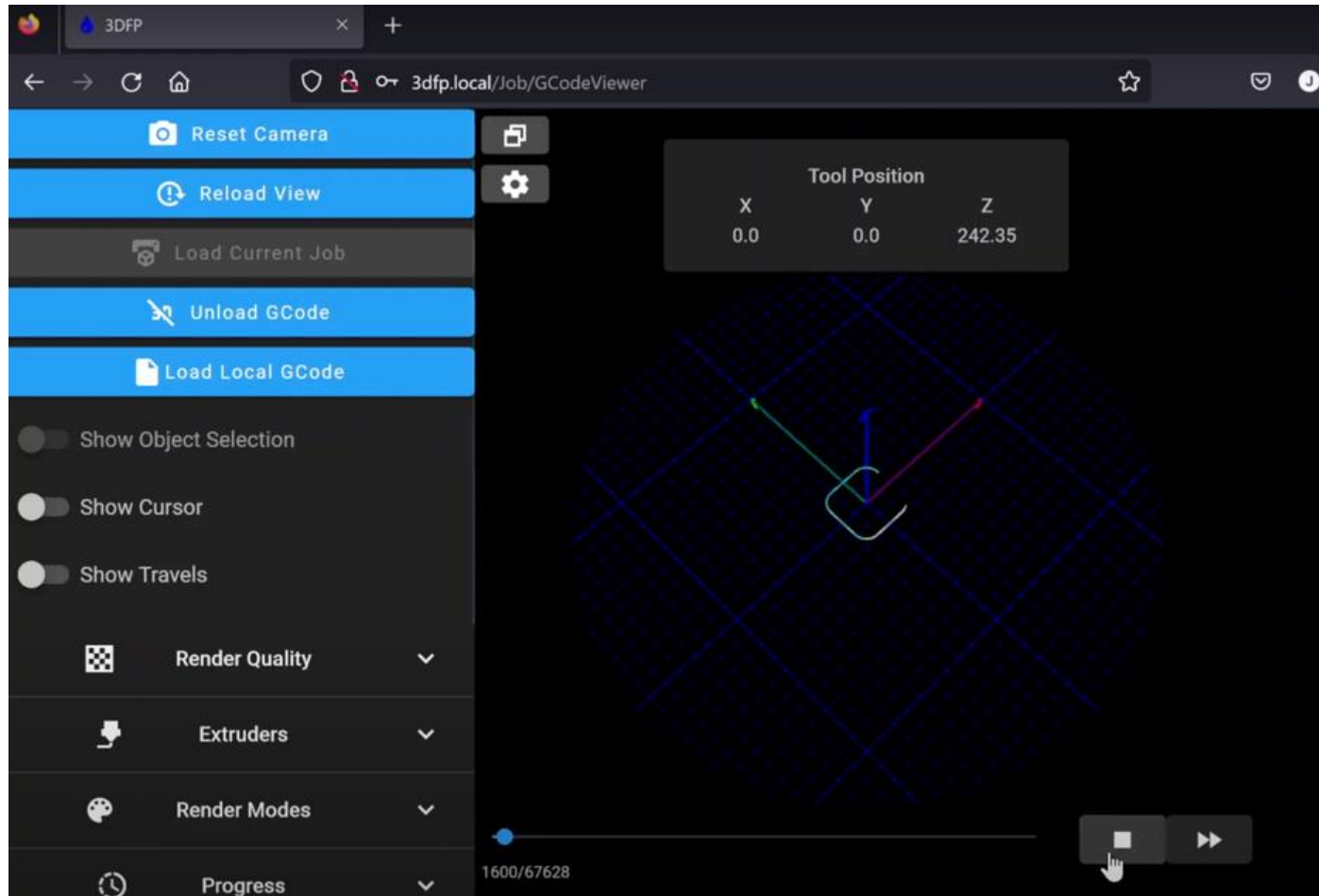


Figure 40 - Changing the Increments on Dashboard of Duet Web Control

Additionally, there are several plug-ins that are packaged with DWC such as Height Map, Object Model Browser, Accelerometer, etc. However, there is also an option to upload any open-source plug-ins found by the user. The plug-in we found to be most helpful was the G-code Viewer—a plug-in to virtually simulate the printer’s tool pathing (dry print). Figure 41 shows a test dry-print being run on the G-code Viewer.



*Figure 41 - Initial Tool Path of 1x1x1 Cube on G-code Viewer*

There are additional customizable settings under the General Settings tab in DWC. These features include a choice between light-mode or dark-mode for the DWC UI. Users can also choose whether to keep error messages on the screen or to have them automatically close after a specific time period. There are many other settings designed to cater to user preferences and can be useful in customizing DWC to suit individual needs. Figure 42 shows different settings available to be set by users.

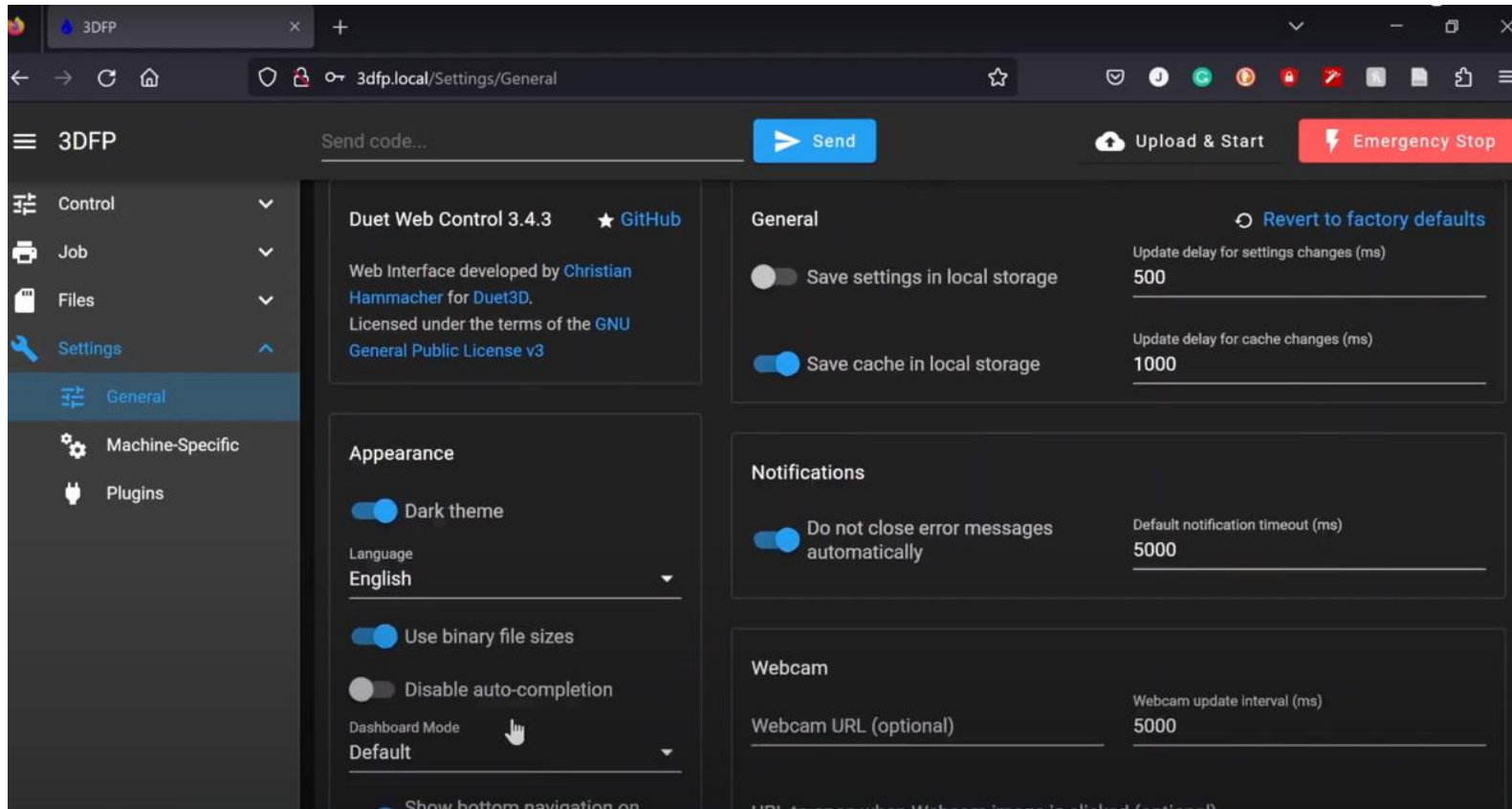


Figure 42 -Customizable Settings for Duet Web Control

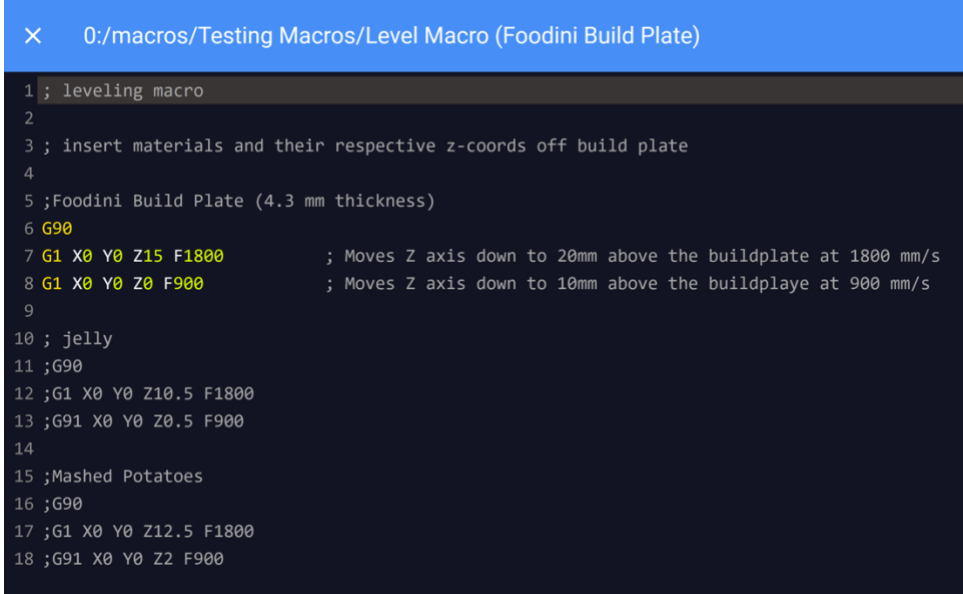
#### 4.7.2 Added Macro Files

A macro file is a text file on the printer's SD card containing sequences of G-code commands, used to automate common tasks. Macros appear as clickable icons on the dashboard in DWC which makes them easy to access. We created several macro files in order to test the printer's functionality and add functionality that could not be captured in the Duet Web Control UI. The macro files execute the following jobs: leveling, homing of the printer and the extruder, filament material property testing, priming the syringe, and shutting down the printer.

##### *Leveling Macro:*

The DWC UI has a prebuilt leveling feature that uses a z-probe. Since our printer was not designed with a probe, we created our own macro that hard codes (sets in the program a specific value and requires modification of the code to change) the position in which the printer head is to lower to when starting a new print.

The purpose of this file is solely for testing purposes. When the macro is run, a single line of G-code is executed, telling the printer what X, Y, and Z coordinate to move the printer head to. These coordinate values are dependent on the thickness of the printing tray being used. As shown in Figure 43, there are several commented-out lines of code in the file that contain the same command but with different Z coordinates depending on the printing tray that is being used. If one tray is switched out for another, the user must comment out the unnecessary lines of code that do not pertain to that tray and uncomment the one that does.



```
0:/macros/Testing Macros/Level Macro (Foodini Build Plate)
1 ; leveling macro
2
3 ; insert materials and their respective z-coords off build plate
4
5 ;Foodini Build Plate (4.3 mm thickness)
6 G90
7 G1 X0 Y0 Z15 F1800 ; Moves Z axis down to 20mm above the buildplate at 1800 mm/s
8 G1 X0 Y0 Z0 F900 ; Moves Z axis down to 10mm above the buildplaye at 900 mm/s
9
10 ; jelly
11 ;G90
12 ;G1 X0 Y0 Z10.5 F1800
13 ;G91 X0 Y0 Z0.5 F900
14
15 ;Mashed Potatoes
16 ;G90
17 ;G1 X0 Y0 Z12.5 F1800
18 ;G91 X0 Y0 Z2 F900
```

Figure 43 - Level Macro (Foodini Build Plate)

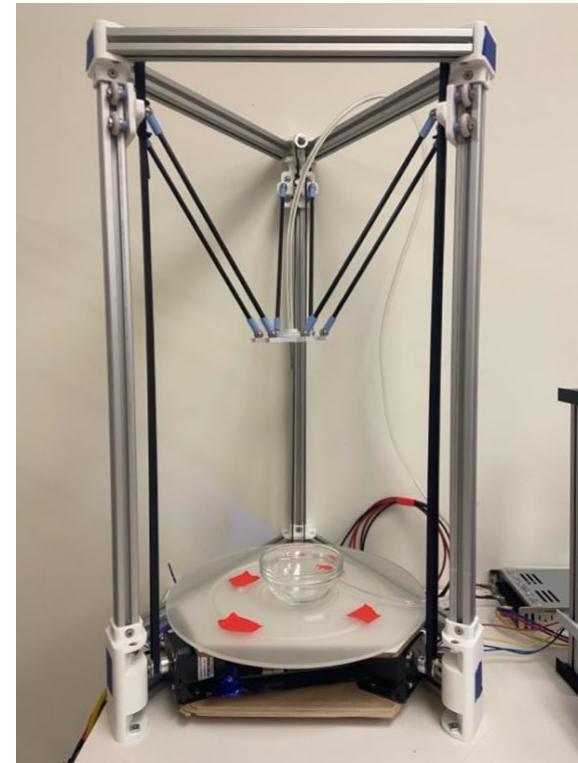
If a thicker tray is used, the printer head must stop at a higher Z coordinate to prevent contact with the tray and potentially break the printing nozzle or the tray itself. With incorrect measurements causing potential damage to the printer, the file should be executed before running an actual print. This macro allows us to ensure the measurements are correct and allow us to be ready to stop the printer in a timely manner if necessary, using the Emergency Stop UI button.

##### *Home Printer Head Macro:*

We developed two homing macros for our printer. The first one, “Home Printer Head”, is responsible for homing specifically the

printer head and nozzle. This macro is called in place of the UI's prebuilt "Home" button and is designed to be used whenever the user wishes to move the printer nozzle/head out of the way and into its "resting" location. This macro homes the printer head when endstops are not present. We maintained this macro as it provides a backup if endstops fail.

The file returns the printer head to a centered position at the top of the printer as seen in Figure 44 and Figure 45. Rather than using endstops to detect when the printer head has reached the top of the Z axis, the homing file determines its stopping point based on a specific (X, Y, Z) coordinate. When the printer initially turns on, it is expected to be in its homed position. Then, when the printer turns on (the config.g file is run), the current position (0, 0, <max-height-of-printer>) is set. Now whenever the homing macro is executed, it will send the printer to the known coordinate (0, 0, <max-height-of-printer>).



*Figure 44 - Printer Head in its Homed Position*

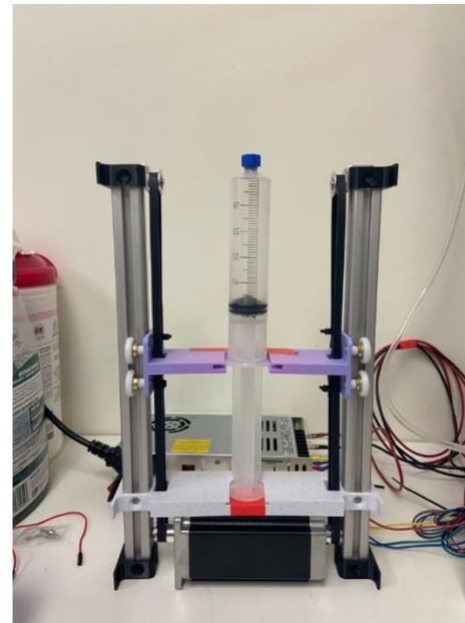
```
0:/macros/Required Macros/Home Printer Head ? G-Code Reference Save  
1 G90  
2 G1 X0 Y0 Z{move.axes[2].max} F2200  
3  
4 ;G90 ; Relative positioning  
5 ;G1 X0 Y0 Z240 F2200 ; Moves to the position that is set at X0, Y0, Z255 (This is our "home" position) at 1800 mm/minute??
```

*Figure 45 - Home Printer Head Macro*



### *Home Extruder Macro:*

The “Home Extruder” is responsible for “homing” solely the extruder. The new macro is called whenever the user wishes to place a syringe into the extruder that is fully drawn and ready to be extruded. Rather than using the UI buttons to retract a desired number of millimeters, the homing file moves the syringe body platform to a preset position in which a new syringe can easily be mounted (Figure 46 and Figure 47).



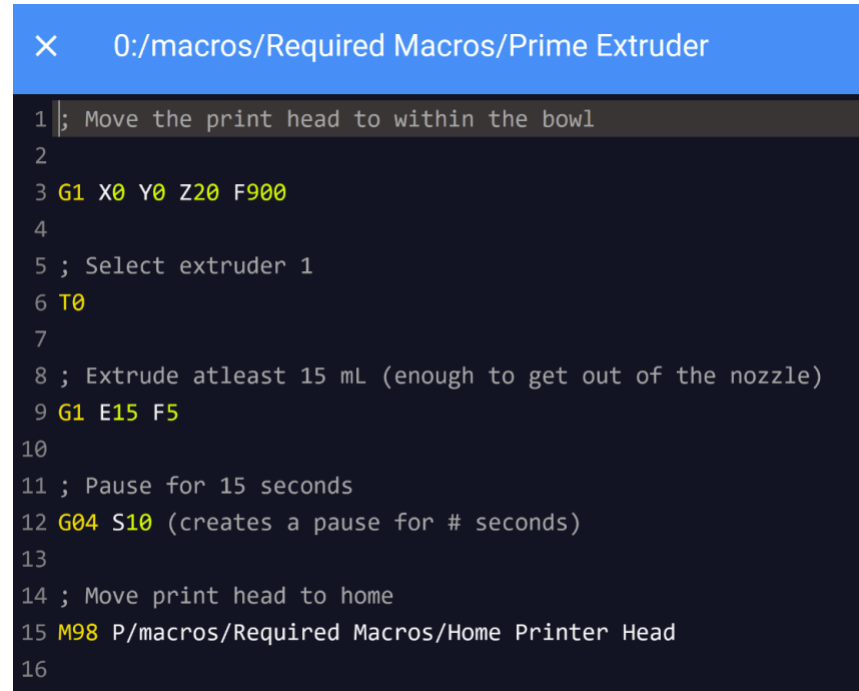
*Figure 46 - Extruder in its Homed Position*

```
0:/macros/Required Macros/Home Extruder ? G-Code Reference Save  
1 |; Based on the object model found (Link 1) and the use of expressions (Link 2),  
2 |; the current position of the extruder is stored in move.extruders[0].position.  
3 |;   Link 1 - https://github.com/Duet3D/RepRapFirmware/wiki/Object-Model-Documentation#moveextruderscurrent  
4 |;   Link 2 - https://docs.duet3d.com/en/User\_manual/Reference/Gcode\_meta\_commands  
5 |; With the position 0, being the "homed" position, we use the negative value of the position,  
6 |; as the distance and direction in which we want the extruder to move.  
7 |  
8 |G1 E{-move.extruders[0].position} F2  
9 |;
```

*Figure 47 - Home Extruder Macro*

### *Prime Syringe Macro:*

The prime macro “primes” the extruder before printing. Priming, in this case, is moving the filament to the top of the nozzle to release any air bubbles. These air bubbles usually get trapped while the tube is prepped with filament. Priming is a crucial step for food 3D printing because it allows for a consistent flow of filament throughout the print. Moreover, this priming macro was necessary to implement because it reduces the amount of time needed for a print. The macro file moves the printer head the height of the drip cup (a glass bowl to catch the extra filament drippage). Line 9 in Figure 48 moves the plunger of the extruder 15 millimeters at a feed rate of 5 millimeters/second which allows for the filament to move through the entirety of the tube and to the nozzle. Once the priming macro has been run, the extruder is ready for the print job.

A screenshot of a code editor window with a blue title bar that reads "0:/macros/Required Macros/Prime Extruder". The code is displayed on a dark background with line numbers 1 through 16 on the left. The code includes comments and G-code commands for moving the print head, selecting the extruder, extruding filament, pausing, and homing the printer head.

```
1 ; Move the print head to within the bowl
2
3 G1 X0 Y0 Z20 F900
4
5 ; Select extruder 1
6 T0
7
8 ; Extrude atleast 15 mL (enough to get out of the nozzle)
9 G1 E15 F5
10
11 ; Pause for 15 seconds
12 G04 S10 (creates a pause for # seconds)
13
14 ; Move print head to home
15 M98 P/macros/Required Macros/Home Printer Head
16
```

*Figure 48 - Prime Extruder Macro*

### *Shut Down Macro:*

Before the printer is shut down, the printer head and the extruder must be homed in order for their numerical positions to be accurate the next time the printer is powered back on. To simplify this process, the “Shut Down” macro was created. This file calls both the “Home Extruder” and the “Home Printer Head” macro files. This allows the user to execute a single file to prepare the printer for powering off, rather than needing to execute several files. Please refer to the following figure (Figure 49) for the code used.

```
0:/macros/Required Macros/Shut Down
? G-Code Reference Save

1 ;3DFP Homing Function
2 ;G90 ; Relative positioning
3 ;G1 X0 Y0 Z240 F2200 ; Moves to the position that is set at X0, Y0, Z255 (This is our "home" position) at 1800 mm/minute??
4
5 ;Extruder Homing Function
6 ;G1 E-10.5 F2
7
8 M98 P/macros/Required Macros/Home Extruder ; Runs the "Home Extruder Test" macro from the "aacros/Required Macros" directory
9 M98 P/macros/Required Macros/Home Printer Head ; Runs the "Home Printer Head" macro from the "aacros/Required Macros" directory
```

*Figure 49 - Shut Down Macro*

## 4.8 YouTube Tutorials

Our video documentation featured two video tutorials which cover setting up the 3DFP and how to use the 3DFP. These videos are titled “Connection Video” and “Basic Duet Web Controls”. Please refer to

Appendix D: Outline for YouTube Channel Tutorials to see the detailed outlines made before filming each of these tutorials.

For each of the videos, we screen-recorded our laptop screen while talking through the steps we listed in our outline. Using this method allowed for the editing process to be easier since both the visual and the audio recordings lined up seamlessly.

We used iMovie as our editing tool since we needed to simply cut, paste, or rearrange audio and video recordings. To add some finishing touches, we overlaid some light music in the background as well as an intro and outro with the logo we created. Figure 50 shows the editing process for each of these tutorials.

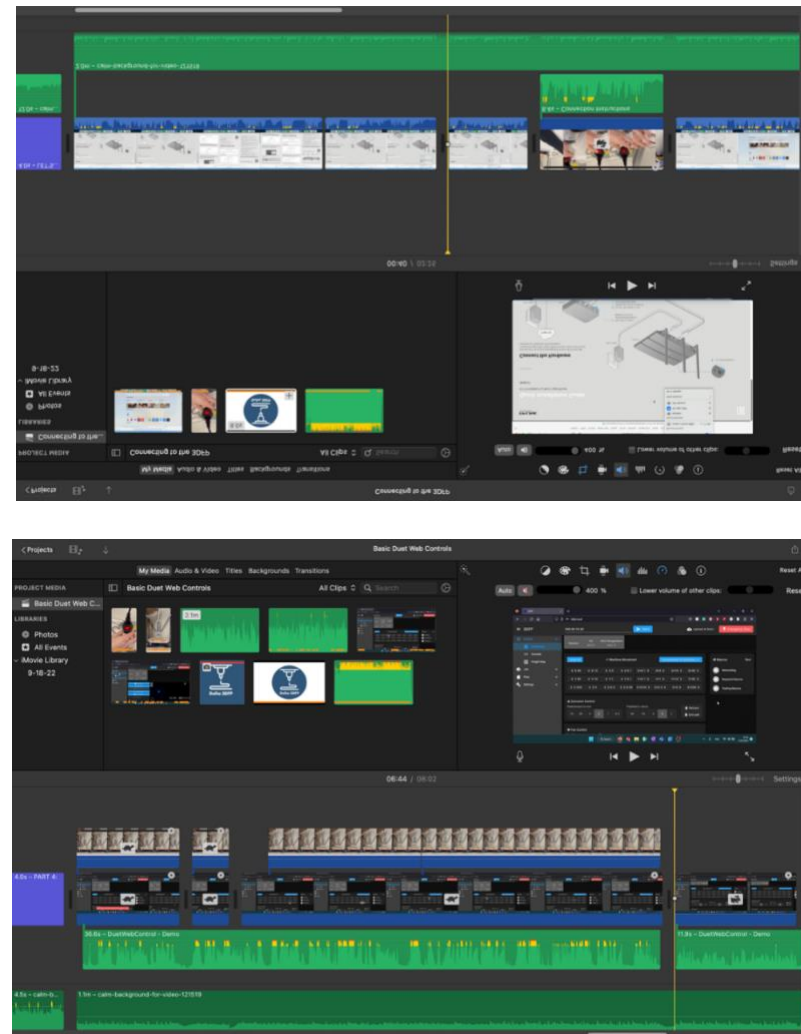
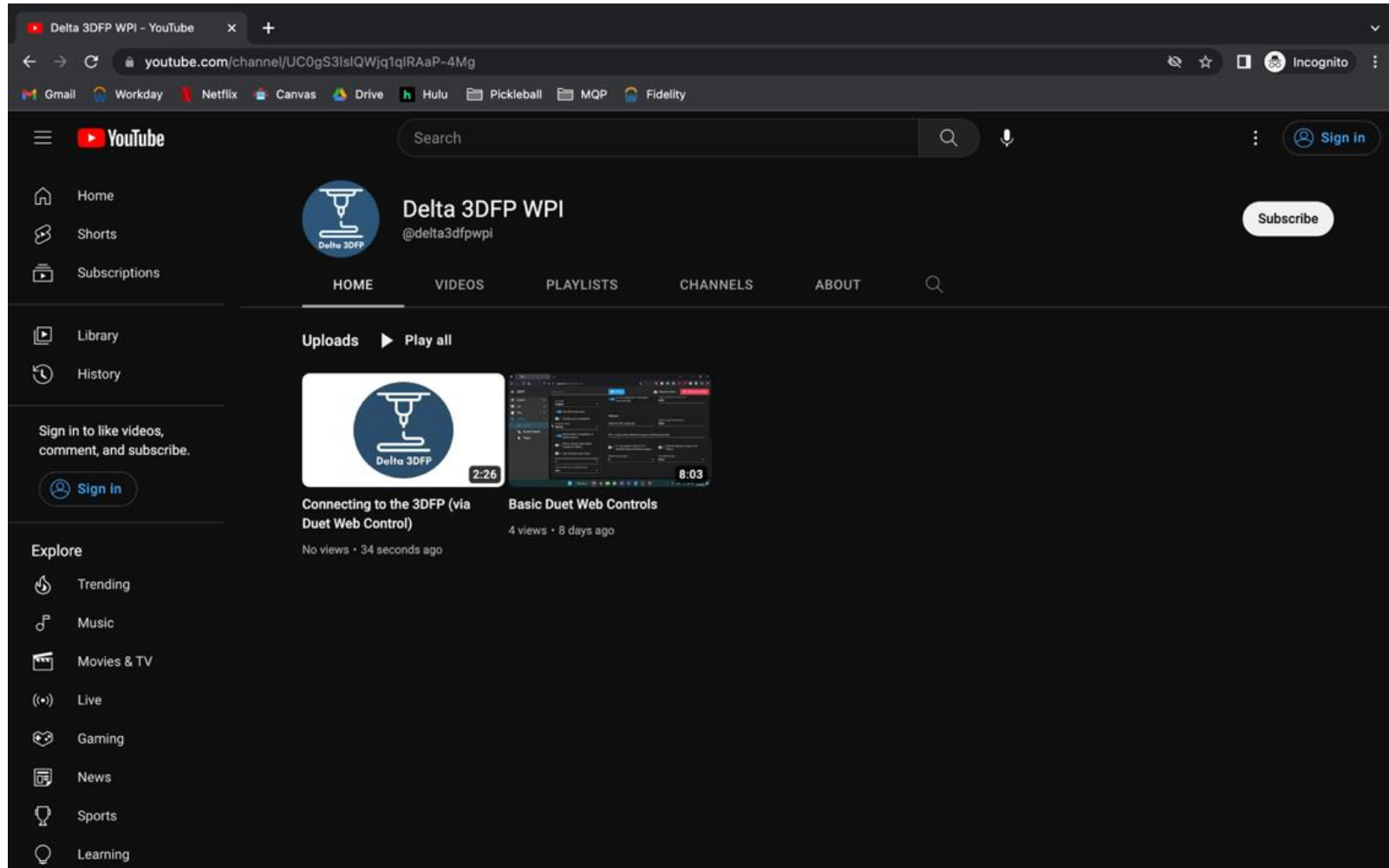


Figure 50 - Editing Process

The final step was to upload both these tutorials to a YouTube Channel for ease of access. We named our channel “[Delta 3DFP WPI](#)”. Please see Appendix E: QR Code for YouTube Channel for the QR code which can be scanned and will redirect you to the YouTube

Channel. We uploaded both our tutorials ensuring to give our videos descriptive titles and specific descriptions. Figure 51 shows the videos featured on our channel.



*Figure 51 - Delta 3DFP WPI YouTube Channel Published Videos*

## 5.0 Conclusion and Future Recommendations

Through the exploration of this project, we have learned a vast amount about 3D Food Printing. In addition to making significant progress, we have also arrived at a number of key findings and would like to present recommendations for the benefit of future groups working on this project.

### 5.1 Extruder

Throughout the duration of this project, we produced multiple designs of the extruder to create consistent extrusion. Along with designing multiple extruder systems, we conducted research on pre-made extrusion kits that can be integrated into our 3DFP. However, due to supply chain issues, we were unable to purchase and implement an extruder system successfully. Below, we have listed, in detail, a few options which we deemed compatible with the 3DFP. These serve as future avenues, which require more research but will aid in continued progress on this project.

One approach would be to continue to redesign the extruder system. Based on our team's attempts to design an effective extruder, we believe future avenues of research could be an extruder powered by air compression or investigating different motor types and gear ratios. Between these two avenues, we believe a group of students could design their own 3DFP extruder focused on food materials.

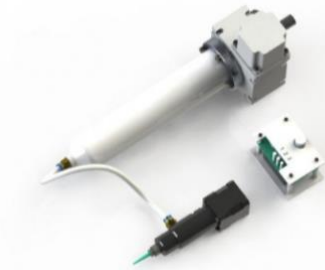
Another approach would be to purchase a ceramic printing kit. Based on our research, we found the Eazao Ceramic Extruder Kit to be compatible with our 3DFP. This kit will function separately from the printer. The kit has its own motherboard and power supply, thus, allowing the extruder to operate in tandem with the Duet 2 Ethernet board ([“Ceramic 3D Printer Kit | Eazao Kit,” 2021](#)). Figure 52 shows the Eazao Kit. Similarly, the Cerambot Ceramic Extruder Kit introduces an extruder system that operates separately from the main motherboard of our 3DFP ([“Ceramic 3D Printer Kit | Eazao Kit,” 2021](#)). By operating separately from the Duet board, these are viable avenues for an extruder that will integrate into our 3DFP ecosystem. However, these kits introduce larger nozzles and tubes than the designs we have made for an extruder system, thus significant mechanical updates to the 3DFP are necessary before implementing either of these kits. Figure 53 shows the Cerambot Kit.



*Figure 52 - Eazao Ceramic Extruder Kit*

*([“Ceramic 3D Printer Kit | Eazao Kit,” 2021](#))*

*(“CERAMBOT Pro Extruder Kit,” n.d.)*



*Figure 53 - Cerambot Ceramic Extruder Kit*

## 5.2 Endstops

To explore the relationship between DWC and endstops, we added endstops to the top of our printer. However, our implementation was in the prototyping phase as they were not permanently affixed to the device. We recommend that future groups conduct a more extensive investigation into the relationship(s) between endstops and DWC functions. It is highly recommended that a secure fixture point be created for the endstops to ensure consistent activation.

## 5.3 Next Steps

Among other areas that need further exploration, we note DWC’s filament profiles. DWC allows users to create different filament profiles; however, the way these profiles are created and used needs to be researched. Therefore, we recommend that future groups not only investigate different ways to create these different filament profiles, but also research material properties such as the viscosities of different food printing materials. We also recommend understanding the relationship between the material properties and the DWC filament properties.

Through the research we’ve conducted in this project, we have acquired vast amounts of knowledge, that oftentimes surpassed our “degree” designations. While this served as a great learning

experience for us all, it also often complicated our processes and approaches to obstacles we tackled. When we had to investigate areas outside of our major(s) we lost time towards first situating ourselves within the field's jargon, and then investigating pertinent areas of concern. We believe, that with a larger and more interdisciplinary group, the scope of this project can expand. We envision this group to merge electrical and computer engineering (ECE), mechanical engineering (ME), computer science (CS), robotics engineering (RBE), and material science and engineering (MME). With a diverse group of students as listed above, we believe this 3DFP can be greatly expanded on.

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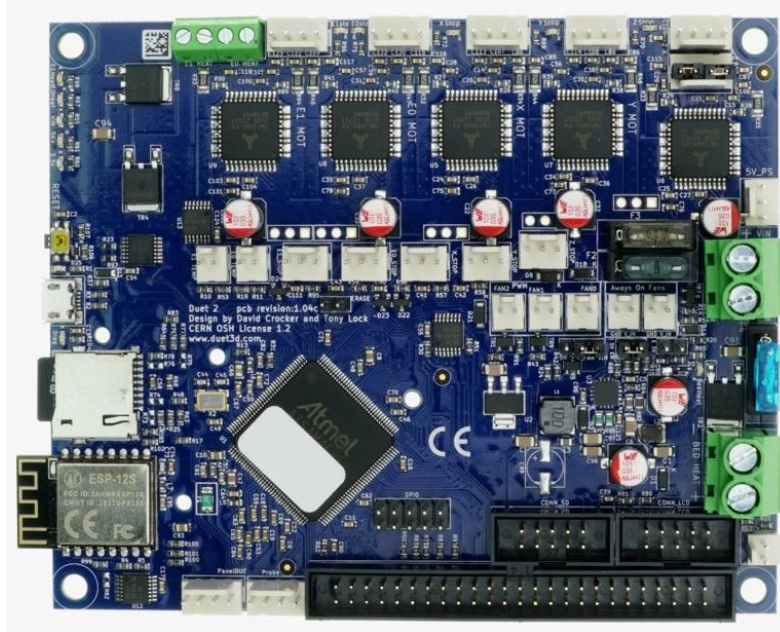
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## Appendices

### Appendix A: Duet 2 Ethernet Motherboard Specifications



*Duet 2 Ethernet Board Purchased for Our Printer*

*(Duet 2 WiFi and Ethernet Hardware Overview, n.d.)*

The following table was taken from Duet3D Documentation, describing the specifications of the Duet 2 Ethernet board (*Duet 2 WiFi and Ethernet Hardware Overview, n.d., p. 2*).

Hardware Specifications	
Processor	<a href="#">ATSAM4E8E</a>
Processor features	120MHz ARM Cortex M4F, 512Kb flash, 128Kb RAM, hardware floating point (single precision), DMA, 2Kb cache
Networking/Comms	10BaseT/100BaseTX Ethernet; USB port; serial port
On-board Stepper drivers	5 x <a href="#">TMC2660</a>
Stepper driver features	Up to 2.4A peak current, up to x256 microstepping, optional x16 interpolation on x16 microstepping, stall detection
High current outputs	1 x 15A1, 2 x 6A each
Medium current outputs	3 x PWM-controlled outputs, 2 x always-on outputs, voltage selectable between VIN, 5V or external supply (all outputs together); 6 more PWM-controlled outputs on expansion board
Thermistor/PT1000 inputs	3, optimised for 100k thermistors, can support PT1000 sensors with reduced accuracy
Inputs/Outputs	5 on-board I/O connectors for endstop and filament monitors (STP pins are 8V-tolerant on revision 1.04 and later), 7 more on expansion header
Endstop or filament monitor inputs	See under Inputs/Outputs
Z probe connector	4-pin with IN/GND/MOD/3V3 pins (IN pin is 30V-tolerant in revision 1.04 and later)
Endstop status LEDs	Yes
Power monitoring	VIN voltage and input to on-board 5V regulator, allows for state save on power failure.

SD card interface	On-board high speed (20Mbytes/sec) SD card socket.
<b>Expansion</b>	
Support for attached Raspberry Pi or other Single Board Computer (SBC)	Yes, from RRF 3.2 (requires hardware modification/additional hardware)
External stepper driver support	Up to 7 external stepper drivers when not using Duex expansion board. Signal levels are 3.3V. A 5-channel expansion breakout board is available to level shift them to 5V.
Stepper driver expansion	Up to 7 additional stepper drivers, of which up to 5 can be TMC2660, as offered by optional <a href="#">DueX5 expansion board</a>
PT100 and thermocouple daughter board support	2 boards (4 channels)
Heater/thermistor expansion	5 more extruder heater outputs and thermistor inputs, 2 more PT100/thermocouple daughter boards (4 channels), offered by optional <a href="#">DueX5 expansion board</a>
Servo support	Up to 5 via expansion connector (3.3V drive unless expansion board used)
Servo support	Up to 5 via expansion connector (3.3V drive unless expansion board used)
LCD support	PanelDue colour touch screen; 12864 display using ST7567 controller chip (RRF 3.2 and later)
Other expansion	4 GPIO pins on <a href="#">DueX2 and DueX5 expansion board</a> , 16 GPIO pins on third-party <a href="#">SX1509B-based I/O expansion board</a>
<b>Notes</b>	
1 Note that the board is rated to 18A on the bed heater channel however from version 1.04 forwards they are supplied with a 15A fuse fitted (18A are difficult to source). If you need 18A on the bed heater channel then you need to fit a 20A fuse and take further precautions against over current.	
<b>Operating Limits</b>	
Stepper drivers	Up to 2.4A peak current
Heater outputs	Bed heater up to 18A, 2 x extruder heater up to 6A each
Input power voltage	11V to 25V
Input connector rated current	25A maximum
Inputs/Outputs	STP pins are 8V-tolerant on revision 1.04 and later, Z Probe IN pin is 30V-tolerant in revision 1.04 and later
Fuses	15A for bed, 7.5A for stepper drivers and extruder heaters, 1A for fans.
5V current limit	2.0A total on 5V and 3.3v, including the internal current consumption (around 200-300mA), any PanelDue or other display, and any endstops/Z probes that draw significant power.

## Appendix B: Longeruner Motherboard Specifications



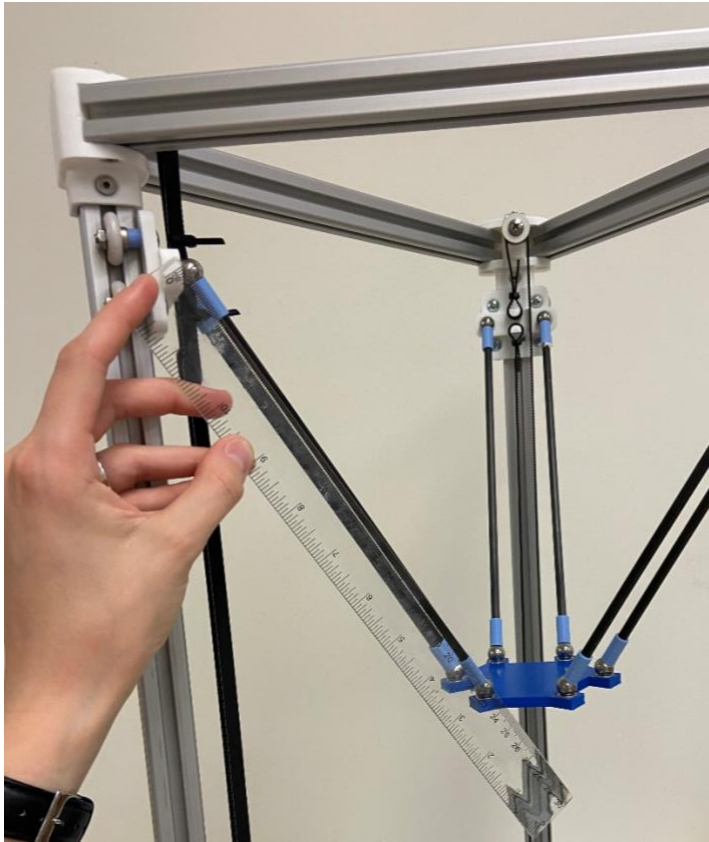
*Longrunner Motherboard*

*(Amazon.Com: 3D Printer CNC Controller Ardiuno CNC Kit with for ArduinoIDE,Longrunner GRBL CNC Shield Board+RAMPS 1.4 Mechanical Switch Endstop DRV8825 A4988 Stepper Motor Driver Nema17 Stepper Motor LKB02,Black : Industrial & Scientific, n.d.)*

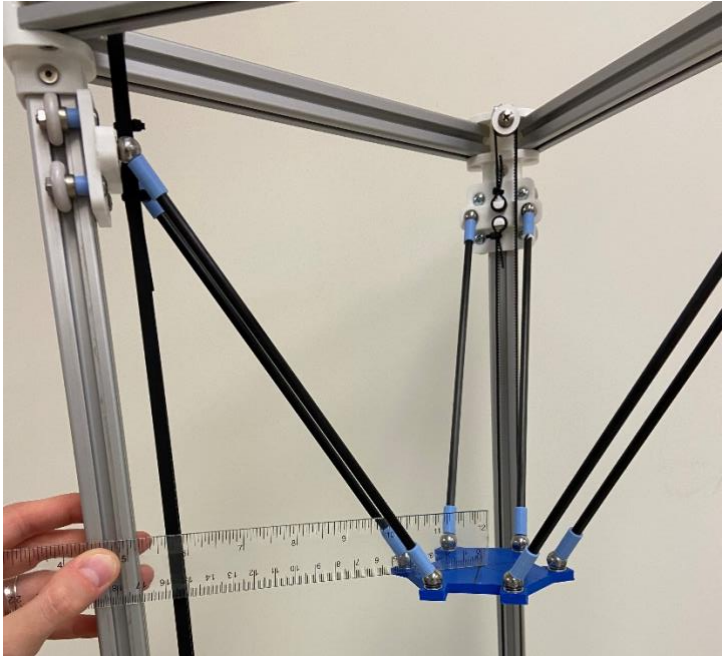
The following table was created based on information taken from the Amazon listing for the Longeruner board that was purchased *(Amazon.Com: 3D Printer CNC Controller Ardiuno CNC Kit with for ArduinoIDE,Longrunner GRBL CNC Shield Board+RAMPS 1.4 Mechanical Switch Endstop DRV8825 A4988 Stepper Motor Driver Nema17 Stepper Motor LKB02,Black : Industrial & Scientific, n.d.)*. The table describes the specifications of the Longeruner board that were available.

Specifications	
MCU	ATmega328
USB interface	ATmega16U2
Operating voltage	5V
Digital I/O pins	14 (including 6 with PWM capability)
Analog input pins	6 I-I/O
pin output current	40mA max 3.3V
output current	150mA max
Flash memory	32 kB (0.5kB used by bootloader - included)
Static RAM (SRAM)	2 kB
EEPROM	1 kB
Clock speed	16MHz

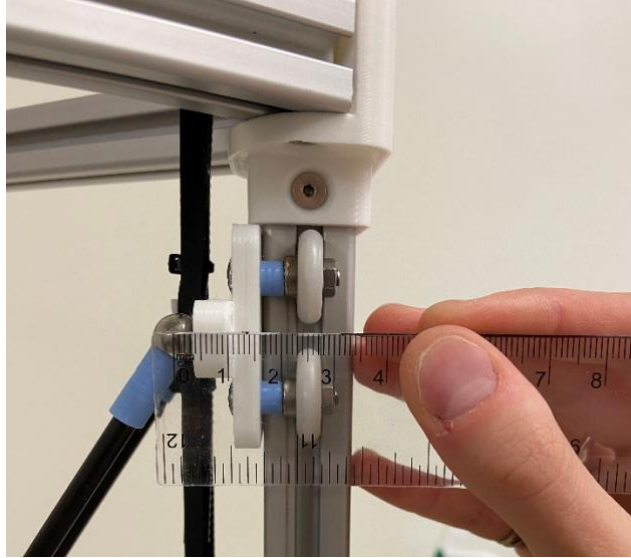
Appendix C: 3D Printer Measurement Photos



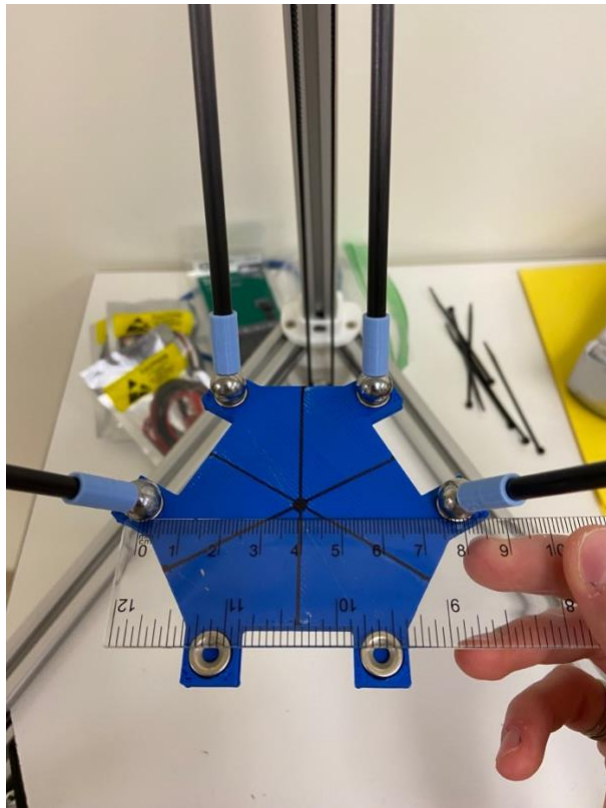
*Diagonal Rod Measurement*



*Delta Smooth Rod Offset*



*Carriage Offset*



*Effector Plate Radius*



## Appendix D: Outline for YouTube Channel Tutorials

The following depicts the [outline](#) for “Connecting to the 3DFP” Tutorial:

*\* Disclaimer this is only needed because we have an Ethernet Duet2 board and thus must establish connection to the Internet via Ethernet (not a Wi-Fi module)*

1. Set up the router as per provided instructions [[Archer C7 Quick Installation Guide](#)]
  - a. Disclaim which exact router we use
2. Connect a machine to the network (preferably one with a SD card reader in case changes to the firmware on the board must be made as this happens without Wi-Fi)
3. Turn on the 3DFP via the power supply
4. Open a web browser
  - a. We’ve had the best experience with Firefox, but Safari also works
5. Type in “printer\_name.local/”
  - a. Disclaim that using “3dfp.local/” works because we designated it in the config.g file
6. Enter password (if set in [Duet Configuration tool](#))
7. Should be connected to Duet Web Control!

The following depicts the [outline](#) for “Basic Duet Web Controls” Tutorial:

1. Turn Machine on
2. Connecting to Motherboard/Duet
3. Introduce overall layout
  - a. On the dashboard, there is helpful information about the machine. Users can see the exact coordinate location of the tool head. If there is an extruder present, users can see the position of the tool as well as speed and sensor information.
  - b. When you first log in you will see the dashboard page. The left-hand sidebar features the Control drop down.
    - i. This drop down features the console which displays the output messages of the machine when snippets of G-code are sent directly.

- ii. Next, there is the height map widget which displays the offsets. This should only be used when the printer uses a probe, which the printer currently doesn't have.
  - c. The next drop-down is called Job which provides key details of any print jobs run by the printer.
  - d. Next, we have Files which has the filaments module. This module allows users to create filament profiles that store key mechanical properties of the materials.
    - i. There is also a section for any G-code print files called Jobs. This is where any of the prints that have been ran previously are stored.
    - ii. Another important feature is the Macro window. This pane is where user made executable G-code files are stored. Macros can be helpful for providing more utility to the machine.
    - iii. Finally, we have a system tab which holds any system files are stored. These files include the printer configuration file.
  - e. Finally, we have the Settings drop-down.
    - i. There are general settings that allow users to see the Duet Web Control version number and other UI based settings.
    - ii. The "machine specific" option displays customizable printer options to heat the bed of the printer or change any other printer machine settings.
    - iii. Lastly, there is a plugin page which shows different tools that work with duet web control.
4. The most important page on the Duet Web Control is the dashboard. From here you can control the printer using the machine movement widget. This allows users to control the x, y, and z axes of the printer. To change any of these incremental values, right click and enter your desired value into the pop-up window and press "Ok".
- a. [Demo here](#)
5. The next widget that is important to note is the macro pane. This provides easy access to any of the user made macros and is helpful for batch running any commands you have created.
6. Next, we have the extrusion control widget which allows the user to control the extruder. Here users can retract or extrude material in increments. Again, users can change these increments the same way we showed before.
7. Finally, we have two important buttons. The "upload and start" button on the upper right-hand corner of the screen allows users to upload a print job which starts right away. The "emergency stop" button should be used when users need to stop the printing job right away.

## Appendix E: QR Code for YouTube Channel

The following image is a QR code which, when scanned, will redirect the user to the YouTube Channel which contains the Duet Web Control tutorials.

