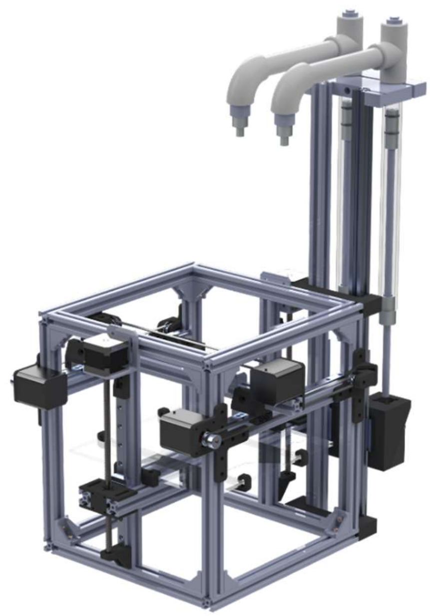
3D Printing with Liquid Silicone



A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

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Report Submitted to:

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Abstract

With the ongoing evolution of 3D printing, the task presented in this project offered a unique challenge to explore the mechanics of these devices and the implementation of a new printing material. The objective of this project was to design and prototype a 3D printer that fabricates parts using flexible silicone. Through iterative design, the team created a mechanically functional printer. The initial phases of design included creating CAD models and assemblies to be manufactured. These designs translated to the physical product with two main sub-assemblies: a typical 3D printer chassis with X, Y, and Z-axis motion and a dual-piston extruder, which mixes two-part curing silicone as the device's build material. To expedite the curing process, a system was implemented to continuously distribute heated air around the end effector. In the final stages of testing and development, the team continued to refine optimal print settings to ensure quality silicone products.

Acknowledgements

This project would not have been possible without the assistance of Professor Joe Stabile. We thank him for promoting an innovative approach to the Major Qualified Project, where we were able to focus on designing and prototyping in hardware space early in the year. We would also like to thank Professor Stabile for constantly checking in on us inside and out of the project. He played an instrumental role in the success of our project, team, and senior year.

Additionally, we would like to extend our gratitude towards the 2020-2021 3D Printing with Liquid Silicone team. They laid the groundwork for this project. Their research and prototype allowed us to identify strengths and improvements to be made in our rendition of the printer.

Lastly, we are appreciative of all our professors and peers who have academically challenged us to become the critical thinking and problem-solving engineers that we are today.

Table of Contents

Table of Figures

Table of Tables

Executive Summary

The development of additive manufacturing over the course of the last decade has changed the way we develop, prototype, and manufacture products. The Macrothink Institute credits the 3D printing evolution as a "new industrial revolution" due to the portability and compactness of these machines (Feixiang et al., 2016). This revolution has introduced a plethora of common filaments for these printers, with some of the most popular including Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Urethane (TPU), and Polyvinyl Alcohol (PVA) (*Common 3d Printing Materials*, n.d.). To continue propelling this "revolution," new materials must be constantly introduced and tested to expand printing capabilities.

Two-part silicone is an unexplored material frontier. The possibilities for silicone printers' sorts into various categories: medical devices, speaker diaphragms, and gaskets to name a few. Building on an ongoing project, students in the 2021-2022 academic year designed, prototyped, and tested a fully functional prototype 3D printer capable of printing with 2-part Liquid Silicone Rubber.

Figure 1. Final printer render

As the current project developed, the chassis, the extrusion system, and the curing process were selected to hone. To arrive at the refined final product, a design of experiment-style project was utilized by the team. The chassis is reconstructed from aluminum extrusions, creating a sturdier housing for the axis mechanisms. The extrusion system incorporates a replaceable mixing nozzle with motorized pistons to load both silicone parts into the nozzle. The curing system includes a repurposed soldering heat gun which blows hot air onto freshly extruded silicone to expedite curing and allow printing in the z-axis. These three major areas, alongside the implementation of new bed leveling controls and the optimization of printer settings, constituted many improvements this year and have propelled the exploration of two-part silicone as a printing material. On the left is a render of the final prototype.

While printing results are not perfect, they are promising. The heating system was able to cure the liquid silicone in about 15 seconds per layer, much faster than the advertised 30 minutes. When cured properly, the silicone layers adhered to each other to form a homogenous component, and the team was confident that the boundaries between layers would not cause significant stress concentrations or points of failure. Shown to the right is one of the test prints.

Figure 2. Example of a test print

The project largely met its goals in that it successfully produced a 3D printer capable of printing silicone. However, since the team spent a majority of the project on completing and iterating the hardware of the prototype, the first area of improvement is to spend more time optimizing the print settings via a detailed design of experiments. While the printer currently produces promising print results, they leave much to be desired in terms of consistency and accuracy, featuring blobs, inconsistent extrusion, and inconsistent curing. Given more time, the team would be able to find the perfect print settings, improving the consistency and print quality significantly.

The significant achievement of this project was a solid platform with which both this team and future teams can conduct experiments. While the print quality in its current condition is certainly not ready for production use, the curing system works well and produces promising results in terms of layer adhesion and shape retention. The motor system in its current form works flawlessly, providing an excellent foundation for future projects, whether they decide to use this approach to silicone curing or an entirely different one.

1. Introduction

The development of additive manufacturing over the course of the last decade has changed the way we develop, prototype, and manufacture products. The Macrothink Institute credits the 3D printing evolution as a "new industrial revolution" due to the portability and compactness of these machines (Feixiang et al., 2016). This revolution has introduced a plethora of common filaments for these printers, with some of the most popular including Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Urethane (TPU), and Polyvinyl Alcohol (PVA) (*Common 3d Printing Materials*, n.d.). To continue propelling this "revolution," new materials must be constantly introduced and tested to expand printing capabilities.

Two-part silicone is an unexplored material frontier. The possibilities for silicone printers' sorts into various categories: medical devices, speaker diaphragms, and gaskets to name a few. To kickstart this investigation, a 2020-2021 MQP team began by creating the first rendition of a 3D printer using silicone. The group selected two-part, platinum-based silicone, which continued to be used through this year's continuation of the project. Some other key parts of their prototype included a 3D printed screw (*Figure 3*). The two silicone parts were manually entered with syringes and mixed through the motorized screw (*Figure 4*). The printer chassis was primarily made of 3D printed parts and wood.

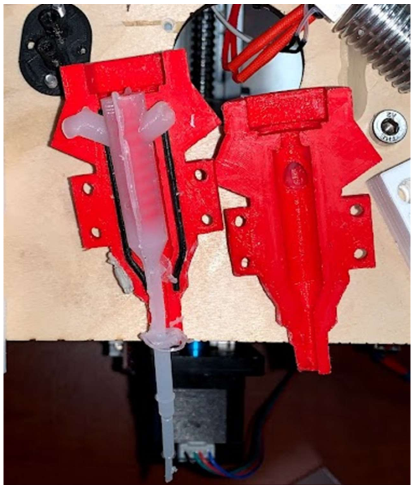

Figure 3. The inside of the 3D printed mixing screw. Cured silicone is inside the screw housing, covering the screw.

Figure 4. Manually entering silicone parts A and B using syringes.

As the current project developed, the chassis, the extrusion system, and the curing process were selected to hone. The new chassis is reconstructed from aluminum extrusions, creating a sturdier housing for the axis mechanisms. The extrusion system incorporates a replaceable mixing nozzle with motorized pistons to load both silicone parts into the nozzle. The curing system includes a repurposed soldering iron which blows hot air onto freshly extruded silicone to expedite curing and allow printing in the z-axis. These three major areas, alongside the implementation of new bed leveling controls and the optimization of printer settings, produced a mechanically functional prototype that has propelled the exploration of two-part silicone as a printing material.

2. Background

2.1. Silicone Rubber

Silicone is a man-made polymer chain that was first discovered by English chemist Frederic Stanley Kipping in 1927. Whilst most polymers are long chains of carbon, silicone has a backbone of element silicon and oxygen atoms. This helps strengthen the bonds but also allows for flexibility at a molecular level. Because of this, silicones have some of the lowest glass transition temperatures and the highest permeability to gasses compared to other polymer chains. Silicone also has a high tensile strength, flexibility, and hardness which makes it valuable in many applications.

The auto industry has adopted many forms of silicone due to electrical-insulating properties, heat resistance, and chemical stability. Because of this, gaskets, O-rings, and heat resistant seals all use some form of silicone rubber. Pre-molded silicone gaskets, in specific, have been effective in sealing engine components (Roberts, 1990). Silicone has also been used in medical applications such as airways, feeding tubes, ear plugs, infusion sleeves, shunts, implants and more (*Silicone Rubber for Medical Device Applications*, 1999). Its chemical stability allows for easy cleaning and sterilization through many different methods.

Oftentimes, silicone exists as two separate parts and only cures when mixed. Mixing these parts starts a reaction and forms chemical bridges which strengthen the rubber and hold it together. There are a few different types of curing systems, and each have their own pros and cons. A platinum-based cure system or "addition system" (*Britannica Library*, n.d.) is when the polymers in each of the parts react with a platinum complex catalyst to create an ethyl bridge. This process cures relatively quickly however, the presence of other elements can cause impurities in the curing process. Moreover, the reaction can be accelerated with the addition of heat.

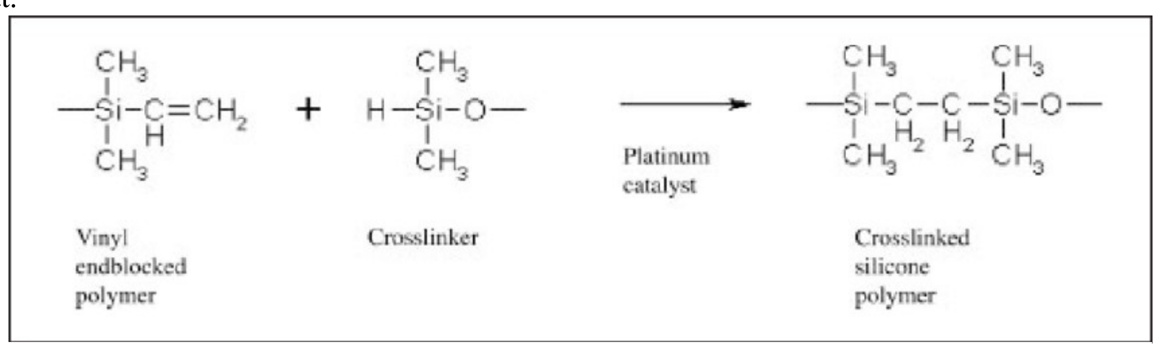

Figure 5. Curing reaction of platinum-based silicone.

2.2. Current State of 3D Printing

3D printing, also known as additive manufacturing, is a form of fabrication that involves adding material at specific locations to form a larger part (*3D Printing*, n.d.). This is opposite of subtractive manufacturing such as CNC milling which takes away material to achieve the desired shape. The main advantages of 3D printing are the ability to make rapid prototypes, minimize waste material, and to create parts cheaply (*What Are the Advantages and Disadvantages of 3D Printing?*, n.d.). Because 3D printers have adapted with modern design software, it's easier now more than ever for a complex design to be brought to the physical.

Modern printers today can take almost any geometry given and print that design in any color or compatible material desired. Printers have gotten so good at replication that larger business operations have been replacing more traditional manufacturing setups like molding and casting into the realm of additive manufacturing. 3D printing now has numerous applications in the medical fields from being used for making tooth fillings, skin tissue or even entire organs (Singh et al., 2015). The food industry has adopted the technology and research in 3D printed food has been a hot topic as of late (Zhang et al., 2021). There have even been attempts at 3D printed housing (*3D Printed Houses by SQ4D Inc*, n.d.). As well as these new and more ambitious applications, 3D printing will always have a place in freelance manufacturing and hobbyists to quick and quality parts and prototypes.

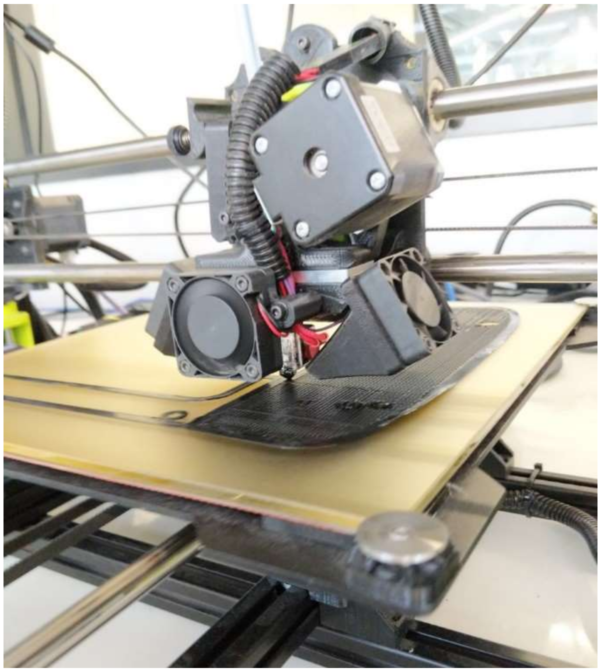

Figure 6. Modern day 3D printer and print

Materials have been an expanding point of research for additive manufacturing. Polymers were the first group of materials to be used as they are relatively strong, malleable when heated and very cheap (Shahrubudin et al., 2019). The first additive manufacturing called fused deposition modelling (FDM) used successive layers of extruded thermoplastic filament to create the third Z-axis geometry seen in 3D prints. Some of these plastics used were polylactic acid

(PLA), acrylonitrile butadiene styrene (ABS), polyethylene (PE) or polypropylene (PP) (Caminero et al., 2018).

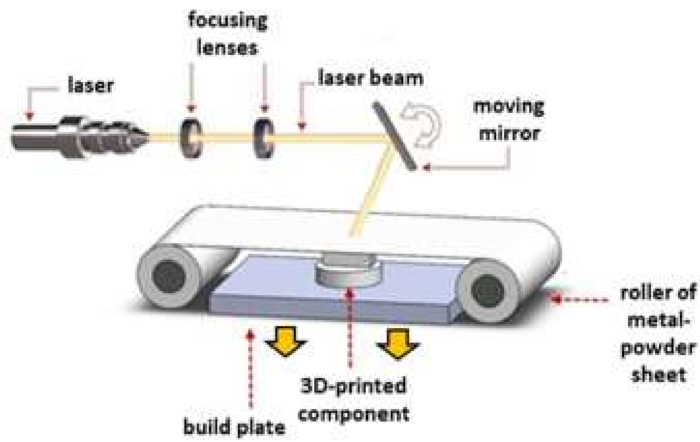

Figure 7. Metal 3D printing using PowderBed Fusion

Another branch of materials being tested are various metals. Metals generally take a lot of heat energy to allow for manipulation. Most metal manufacturing involves heating the metal up either to a liquid state to be poured and cast or to a temperature where it is ductile enough to be forged. One method of printing with metal is to use a technique called PowderBed Fusion (PBF). PBF involves placing a thin layer of powdered metal over a base plate before a high-powered laser welds a point at each layer. Over time, these layers compound and create a 3D part (Lupoi et al., 2022). This process is still being developed.

3. Design Process

The printer is composed of two distinct sub-assemblies which operate in conjunction with one another. These two major sub-assemblies are the chassis and the extruder. The chassis gives structure to the printer as well as positions the print bed and the print head. The chassis of the printer is ultimately what all other parts attach to and be designed around. The extruder is the mechanism which is responsible for mixing and extruding the silicone from the print head. Designing these main assemblies also requires the implementation of control systems.

3.1. Extruder

3.1.1. Initial Iteration

The extruder system is an important part of the printer's successful operation. It must take into account many considerations in order to be functional. At a basic level the extruder system must contain parts A and B of the silicone before transporting them to a mechanism which is able to make an intimate mixture of the two parts, which initiates the curing process. Once the parts have been mixed, the silicone must be extruded from a nozzle mounted to the print head of the chassis to be printed. These requirements for the design end up each being a separate part, or mechanism in the extruder subassembly.

Successfully fulfilling the requirements was easiest when working backwards from the nozzle to the pumping mechanism. From basic testing involving cure times of the silicone, it was apparent that the nozzle should be as near as possible to the outlet of the mixer such that the silicone would not cure prematurely. Premature curing of the silicone would cause a clog in the system, preventing silicone from being extruded, and stopping the print. The simplest solution to this was mounting the nozzle to the mixer to ensure that it would be extruded before it had cured. This creates the requirement that the mixer be small enough and lightweight enough to fit on the print head, leading to the use of a static mixer. Static mixers have two inlets which will accept parts A and B of the silicone, before sending them through a series of baffles inside of a hollow tube. The baffles force the unmixed silicone to follow an arduous path, thus being mixed before reaching the outlet. Manual testing prior to assembling the printer showed that a static mixer was sufficient to mix the silicone appropriately. They were chosen as a method of mixing the silicone because they are easy to mount to the print head, have no moving parts and therefore high reliability, and are inexpensive and disposable. Being easy to replace allows them to be exchanged after each print eliminating clogs due to cured silicone.

A mechanism is required to pump the silicone to the static mixer. This mechanism would have to be bolted to the chassis away from the static mixer and use tubing to transport the silicone to the print head as it would be too large and heavy to be mounted to the print head. The pump must have enough power to impart a high enough pressure to pump the silicone at a high enough flow rate to prevent premature curing in the static mixer. *See Appendix A for initial extruder sketches.*

3.1.2. Second Iteration

The extruder went through 2 iterations, both are based on the same design, with the second iteration seeing features added to increased usability. A piston-based system (shown in *Figure 6*) was chosen to pump the silicone as it met the design requirements without exceeding the project's budget. The assembly consisted of two pistons that would contain Parts A and B of silicone resin and keep them separate until they reached the static mixer.

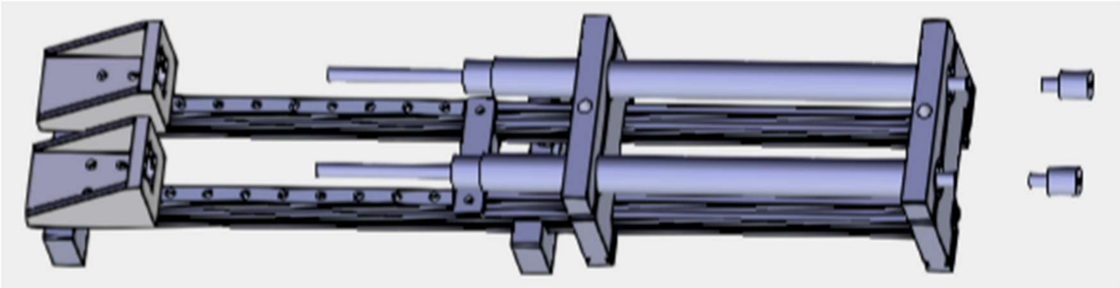

Figure 8. Extruder assembly. The assembly is pictured horizontally, although the final design has it mounted vertically.

The cylinders of the piston assemblies were made of 25mm internal diameter, clear, polycarbonate tubing. Clear tubing was used so that the position of the piston within the cylinder, as well as the silicone resin could be seen. Each piston head featured two O-Rings used to seal against the inside wall of the cylinder as shown on the left in *Figure 9*.

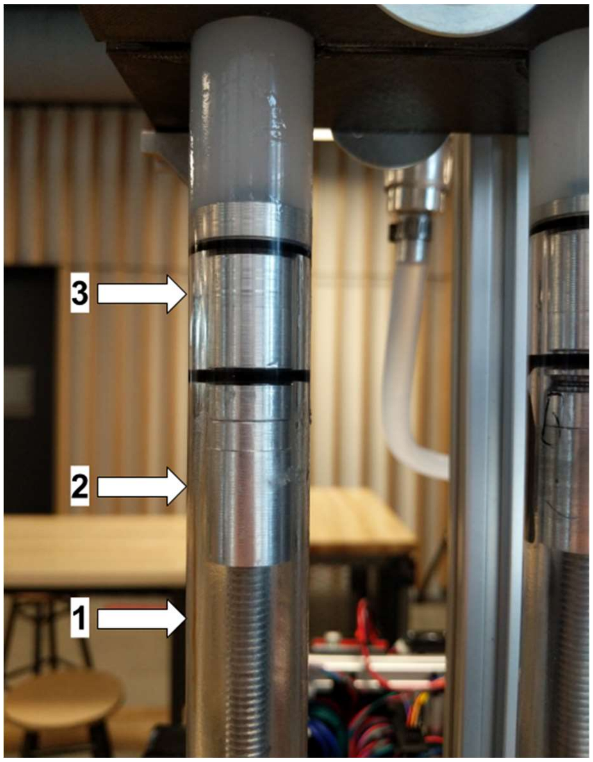

Figure 9. Shown above is the piston head and coupling. The piston head (#3) features two O-Rings which seal against the inside walls of the cylinder. As the piston advances this displaces silicone from the cylinder, towards the end effector. The coupling (#2) sits below the piston head, flush against it. Its purpose is to allow for angular and axial misalignment between the threaded rod (#1) and piston head. It also prevents the piston head from rotating with the threaded rod, constraining its movement to translation within the cylinder.

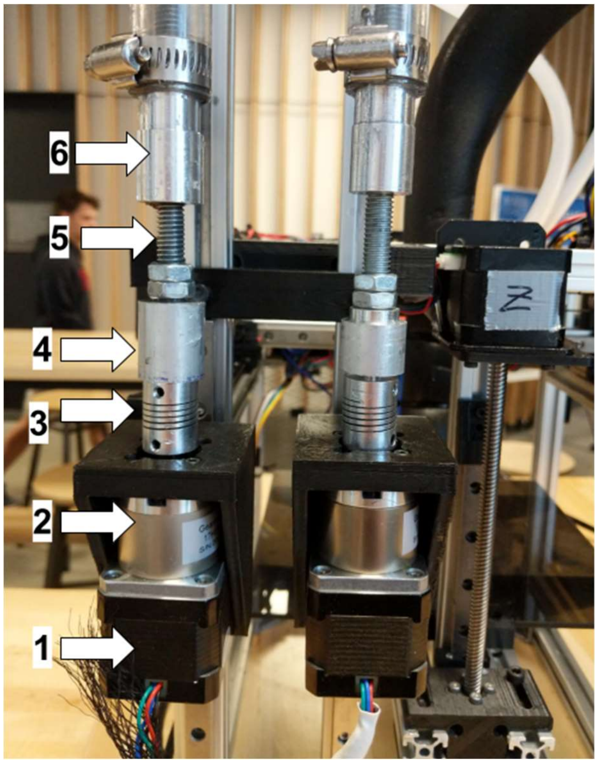

Figure 10. Stepper motors and lower cap of pistons. In the photo the stepper motors (#1) fitted with planetary gearboxes (#2) are shown mounted to their black carriers. This allows them to translate up and down the aluminum extrusions which serve as a frame for the extruder. Flexible disc couplings (#3) are used to transmit torque from the stepper motors to the threaded rods while allowing for angular and axial misalignment. An adapter (#4) is used to fix the threaded rod (#5) to the flexible disc coupling. The lower caps (#6) of the cylinders are threaded so that the threaded rod and motors will advance when the threaded rod is turned. As the threaded rod turns, the pistons are advanced through the cylinder.

The piston heads are advanced using threaded rods which are turned using two NEMA-17 stepper motors with 27:1 planetary gearbox attachment. The gearboxes are used to increase the torque of the stepper motors as testing showed that a NEMA-17 stepper motor alone did not produce sufficient torque to advance the pistons. The threaded rod interfaces with female threads which are tapped into the lower cap of the cylinder. A close-up of these components are shown in *Figure 10*. As the threaded rod advances into the cylinder, the stepper motor advances via a linear bearing mounted to the aluminum extrusions which serve as a base for the cylinder assembly.

The top of the cylinder is sealed using a hollow aluminum cylinder with a hollow boss which allows a ⅜ inch inner diameter, clear, vinyl tube to be attached to the cylinder to transport the silicone. The tubing is held on using a hose clamp which can be easily removed if necessary. The vinyl tubing serves as a flexible coupling to transport the silicone from the stationary extruder to the moving print head. The tubing is also clear so that the user can monitor the system for air bubbles.

A dual syringe body, typically used for epoxy, was modified to accept the vinyl tubing containing Parts A and B of the silicone resin. A standard static mixer is attached to the dual syringe body. Static mixers are more commonly used to mix 2-part epoxies before they are applied to a part. Preliminary testing found that they were able to adequately mix silicone such that it would cure quickly and completely. Prior to entering the static mixer, Parts A and B of the silicone had been kept separate. As the silicone is forced through the baffles of the static mixer, an intimate mixture is created, initiating the curing process. The dual syringe body and static mixer assembly are shown in *Figure 11*.

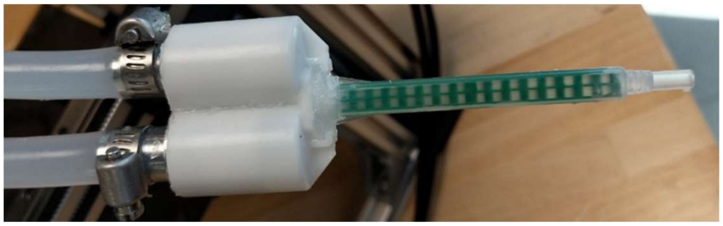

Figure 11. The dual syringe body accepts two vinyl tubes containing separate parts A and B of the silicone resin. To the dual syringe body is a static mixer (green) which is used to mix the silicone such that it will begin curing.

During use of the printer, testing was performed both using a 0.8mm brass 3D printer nozzle mounted directly to the end of the static mixer (*Figure 12*), as well as using the unrestricted nozzle (*Figure 11*) of the static mixer which has a 1.6mm opening.

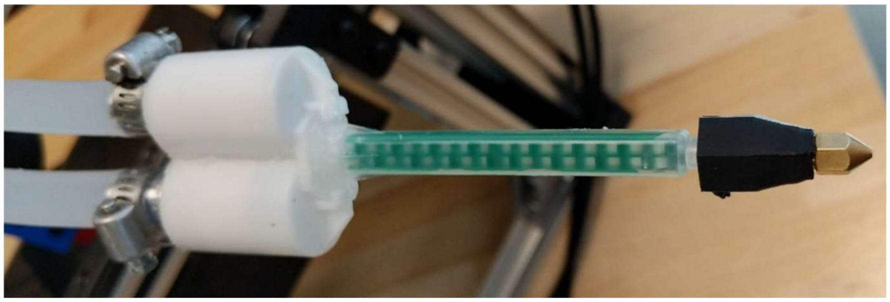

Figure 12. Photo of dual syringe body, and static mixer with 0.8mm nozzle. Not mounted to the printer as pictured.

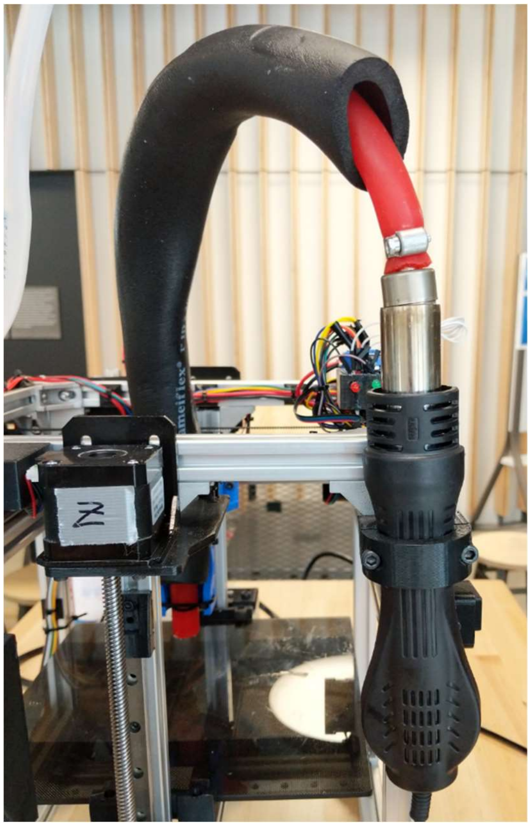

Figure 13. Solder reworking heat gun mounted to the side of the 3D printer with silicone tubing to route airflow. Silicone tubing is encased in insulation to maintain temperature.

During extrusion of the mixed silicone, heated air is distributed in the vicinity of the nozzle. For this, a solder reworking heat gun was used. The heat gun is mounted to the side of the printer (*Figure 13*) and an insulated high temperature silicone hose is routed to the end effector to heat the area and improve air flow. This accelerates the rate of curing of the mixed silicone and helps to prevent unintended flowing of the silicone, as well as increasing possible print speeds.

3.1.3. Final Iteration

Figure 15 is the final version of the extruder. It is identical to the second iteration above except for the addition of a bleed port.

The bleed port was added as a means to not only fill and refill the system, but to purge the system of air bubbles. Air bubbles are undesirable in the system because they will compress under pressure preventing the successful and consistent extrusion of the silicone. Additionally, should an air bubble reach the static mixer, it will prevent the successful mixing of the silicone, preventing curing, and causing a print failure. Each bleed port is composed of a 1-inch PVC T fitting, a 6-inch length of 1 inch PVC pipe, and a 1-inch PVC elbow, as well as a bleed port cap and plug bolt.

Figure 15. Pictured is the final version of the extruder assembly, mounted to the printer. Near the top of the photo are the bleed ports which were added for the final iteration.

The bleed port plug bolt (*Figure 14*) is intentionally located at the highest point in the system to encourage air bubbles to rise to it so they may be released from the system. To purge air from the system, the bleed port plug bolt can be removed, and a syringe (*Figure 16*) filled with the appropriate silicone can be installed in its place. The syringe plunger can be depressed to inject silicone or extended to remove air bubbles. Should a bubble become stuck in the silicone tubing, the silicone, and

Figure 14. The bleed port, which was added the final iteration, is pictured. Specifically, the bleed port plug bolts can be seen at the top of the apparatus. These bolts can be easily removed to reveal a port through which silicone can be added to the system and air can be removed.

bubble, can be pushed through the system using the syringe to evacuate the bubble. Once the bleed procedure is complete, the bleed port plug bolt can be replaced.

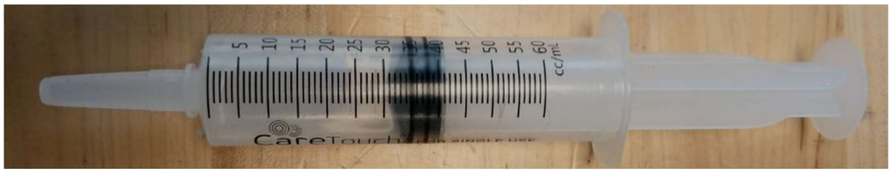

Figure 16. Pictured is an example of a syringe that is used to fill the extruder. With the bleed port plug bolt removed, the syringe can be inserted into the hole that it occupied and used to add silicone or remove air bubbles.

3.2. Chassis

The chassis forms the basis for the motion system of the printer and consists of the X, Y, and Z axis and a cuboid frame. The design chosen was based on the popular gantry-style 3D printer design, in which the end effector moves horizontally in the X and Y directions while bed moves vertically in the Z axis. This design was chosen over other designs where the bed translates horizontally, since it was determined that moving partially cured silicone parts horizontally could potentially cause vibrations, resulting in lower quality parts. Additionally, since the end effector does not move in the vertical direction, any extrusion system would not account for large changes in height, making design considerations for flexible hose routing from the extruder significantly easier.

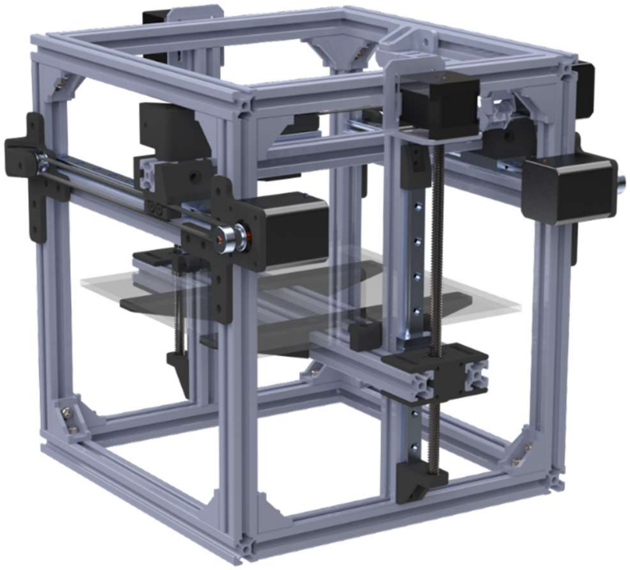

Figure 17. Chassis render

3.2.1. Initial Iteration

An initial chassis design can be seen in the *Figure 18* sketch at right. Before much background research was conducted, a dual bed system was proposed. Each bed would allow for silicone printing, and then would lower into a curing chamber. The second bed was added to allow for multiple prints to happen, so while one bed was curing, another could hold a print. The two beds would operate only in the z-axis. The chassis would operate in the x and y-axes and attach to some form of extruder.

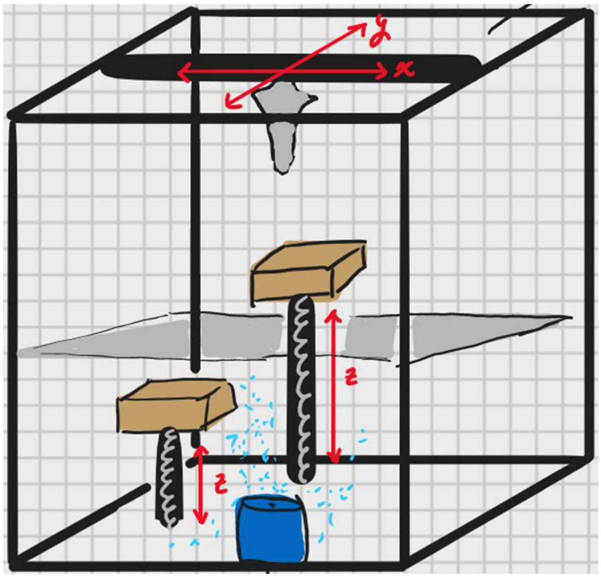

Figure 18. Initial chassis sketch, including a two-bed system

After further research and brainstorming, the chassis evolved into a one bed system without the need of a curing chamber. Aluminum extrusions were chosen as the material of choice for the frame. These extrusions offered a stable and strong platform for the various motors, rails, lead screws, controls, and the extruder system. The aluminum extrusions were also chosen because of their low cost and the simpleness of their assembly.

3.2.2. Second Iteration

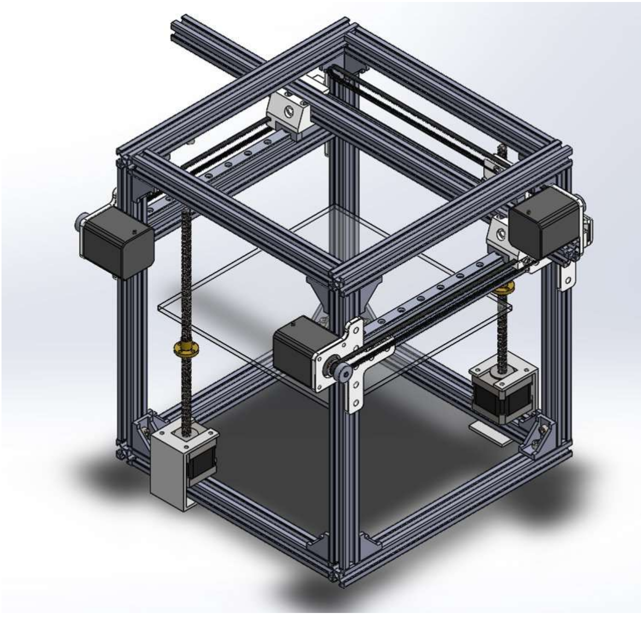

Figure 19. First chassis render in SolidWorks

The x and y-axis mechanisms began their evolution with linear rail bearings attached to dual aluminum extrusions in the x-direction. Each slider has a stepper motor attached to a belt to create the desired linear motion. The y-axis has a single extrusion perpendicular to the x-direction extrusions. The motor attachments are 3D printed with PLA. The 3D printed motor and motor mount are seen in *Figure 20* below. The aluminum extrusion and linear rail bearings can be seen being assembled in *Figure 21*.

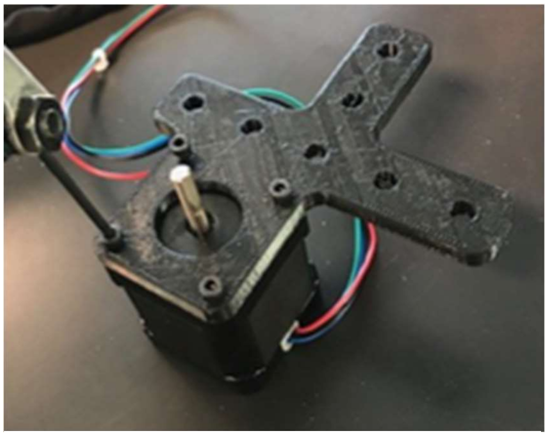

Figure 21. 3D printed motor mount

Figure 20. Aluminum extrusion and linear bearing

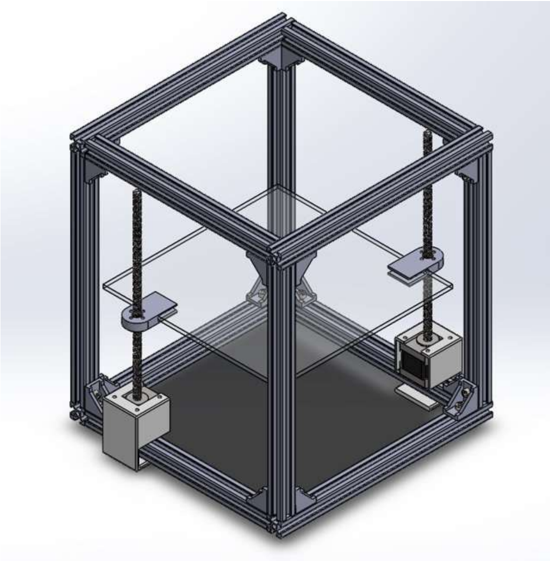

Figure 22. Initial design for Z-axis

The first iteration of the z-axis includes two stepper motors with 8-inch lead screws. These motors will be seen throughout all the z-axis iterations. This model seen in *Figure 22* has the first motor mount concept that was proposed to attach under the aluminum extrusion. These mounts evolve in further iterations because the design does not allow for adequate strength to support the motors because of the weak panels and the material, PLA.

Additionally, the bed supports seen in *Figure 23* are the first iteration of the z-axis fixturing. These supports would attach to the lead screw brass mount. There is an opening that the glass would slide into, and the supports would then translate in the z-axis with the motorized lead screw, ultimately moving the bed.

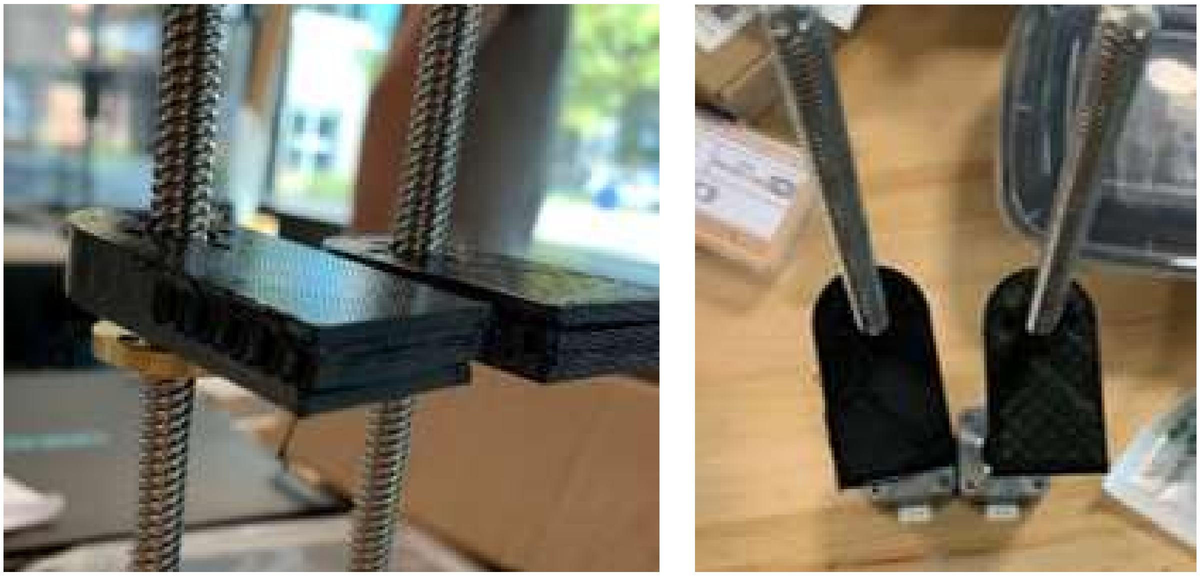

Figure 23. Original Z-axis mount design

3.2.3. Final Iteration

The final version of the chassis consists of a timing belt driven x and y gantry system and a lead-screw driven z-axis. The x-axis is driven with a single NEMA 17 stepper motor, while the y and z axes each are driven by a pair of stepper motors. The final iteration of the x and y axis assembly saw few changes since our initial design, while the z axis was changed significantly.

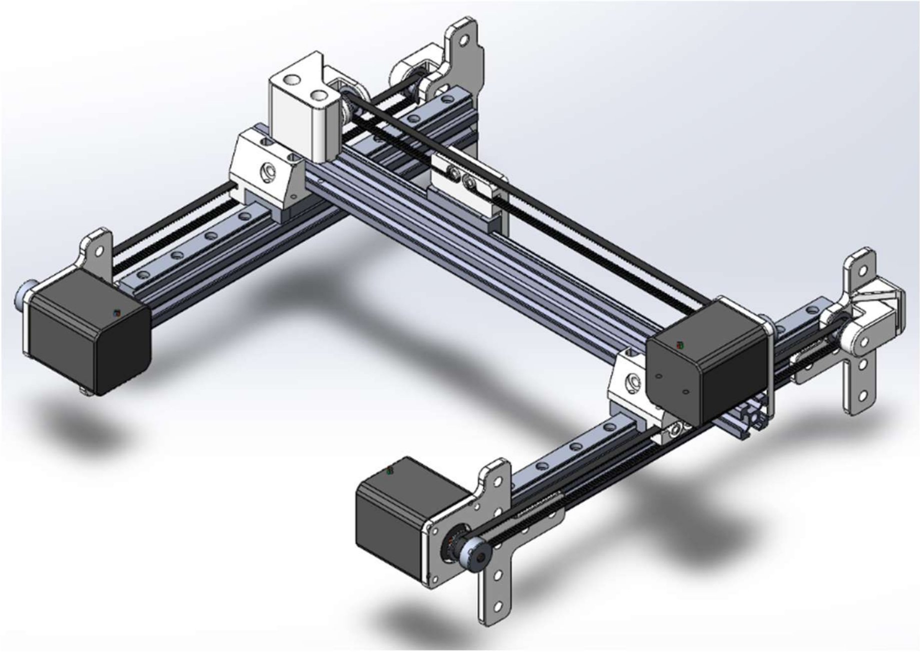

Figure 24. XY subassembly

The X and Y axes were initially constrained using MGN12 linear rail bearings. These ensure complete stability along the range of motion, preventing any unwanted moving or vibration in any direction besides the direction of motion. Given their stability, they are a standard staple of modern industrial machinery and provide an excellent platform with which to build the motion system.

Figure 25. MGN12 Linear Rail Bearing

Since the X and Y axes were driven using belts, tensioning was established early as an important design element. Tensioning ensures that the belts do not skip teeth or develop backlash or other mechanical play in the system. The belt tensioning was accomplished by sliding one of the pulleys in a mechanical track, adjusted with a single M3 Machine screw and captured nut.

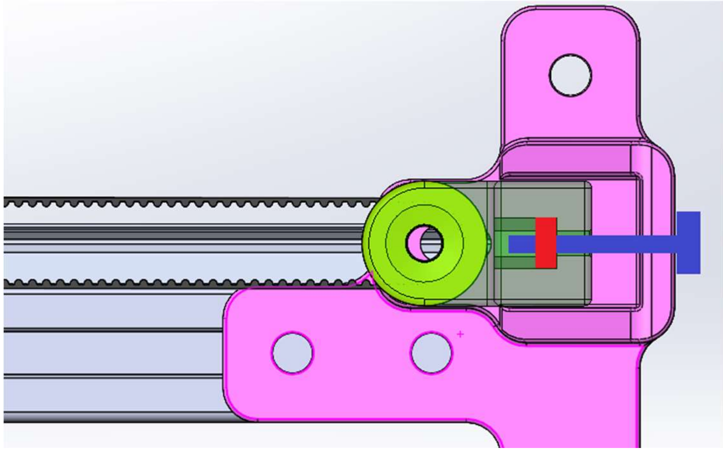

Figure 26. X/Y belt tensioning system. When the screw (blue) is tightened against the captured nut (red), the pulley block (transparent green) slides in the track (pink), moving the pulley (light green) towards the right and tensioning the belt.

After success with the linear rail bearings in the x and y axes, we decided to adapt the z axis to use linear rail bearings, since they provided the necessary stability and rigidity that previous iterations were lacking. The new design still made use of the lead screws, but with proper constraint from the linear bearings, the team found that there was very little play in the system after assembly.

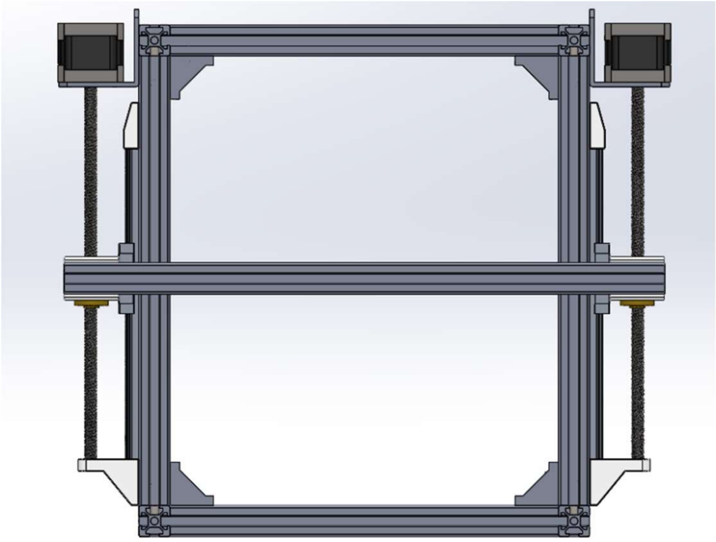

Figure 27. Z-axis side view

The main caveat of a system designed in this way is that the two lead screws have no guarantee of maintaining alignment, since they are only mechanically linked by the horizontal sections of extrusion supporting the bed. This means that we also had to implement a leveling system, which was able to account for and correct any misalignment. The leveling system is described in detail in *Bed Leveler*.

The print bed is a square piece of borosilicate glass designed for use with 3D printers. The team chose this approach in the event of needing to implement a bed heating system for better adhesion. This was ultimately never implemented, since early tests revealed that cured silicone adhered to the bed extremely well even without a heated surface. The glass plate is held in place via a set of clamps, attached near each end of the horizontal cross-supports. This system allows the bed to be removed easily by removing two machine screws on one of the clamps, allowing for easy cleanup and print removal.

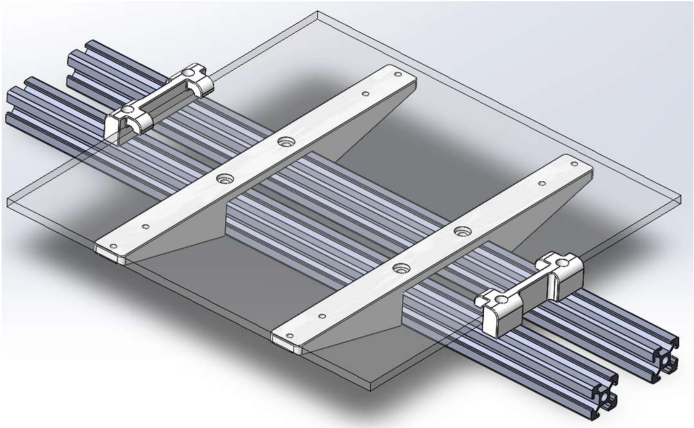

Figure 28. Glass print bed with bed clamps and supports

Each axis has an electrical end stop limit switch, which is used for homing the printer. These are wired using normally closed contact. The switches enable the axes to have a "home" point along their travel distance, which is used by the firmware to determine where exactly within its build space the printer end effector is.

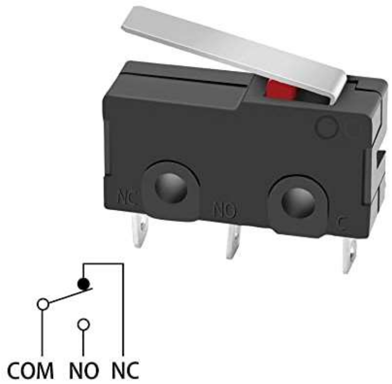

Figure 29. Limit Switch used for end stop (MXRS, 2022)

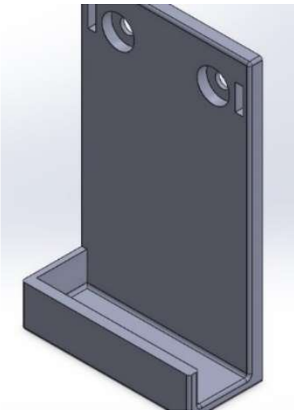

Figure 30. RAMPS board housing

Once the printer was mechanically functional, the design team shifted focus to wire management and electrical housing design. This was essential for easy diagnosis of electrical issues, and was accomplished with cable tie anchors, wire bundles, an energy chain, and 3D Printed PCB mounts.

These features allowed for the routing of the motor cables, end stop signal wiring, power wires, and bed leveler signal wires. The cable tie anchors can retain one zip tie and were designed to fit into the slots of the aluminum 2020 extrusion used for the chassis. They are retained using one button-head machine screw and one tee nut, and also feature small protrusions to prevent rotation.

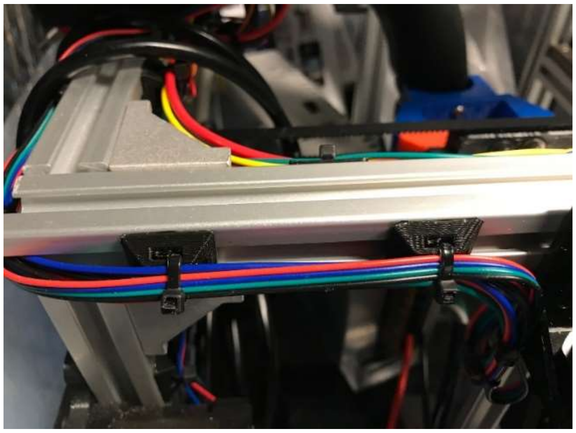

Figure 31. Cable tie anchors

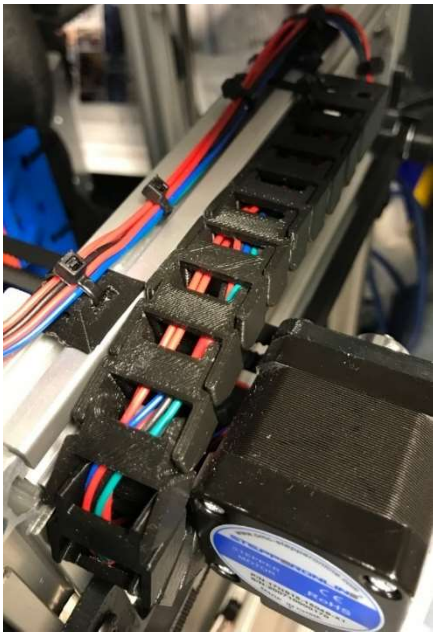

Figure 32. Energy chain

Also included was an energy chain, since the X axis signal wires and motor power cable are constantly in motion any time the printer is moving. The energy chain is a standard design containing 13 links, with custom end links to easily attach to the Aluminum 2020 extrusion.

3.3. Controls

The printer's electronics consisted of the motion controller subsystem, a heating subsystem for dispersing hot air, and a bed leveling subsystem. The motion controls were designed to use standard FDM printer electronic hardware and firmware, the curing system consisted of an off-the-shelf soldering reflow station, while the bed leveler was a custom circuit designed by the team. While these separate systems were almost completely independent, they worked synchronously to ensure proper function of the printer. Below in *Figure 33*, a block diagram describes the entire control system.

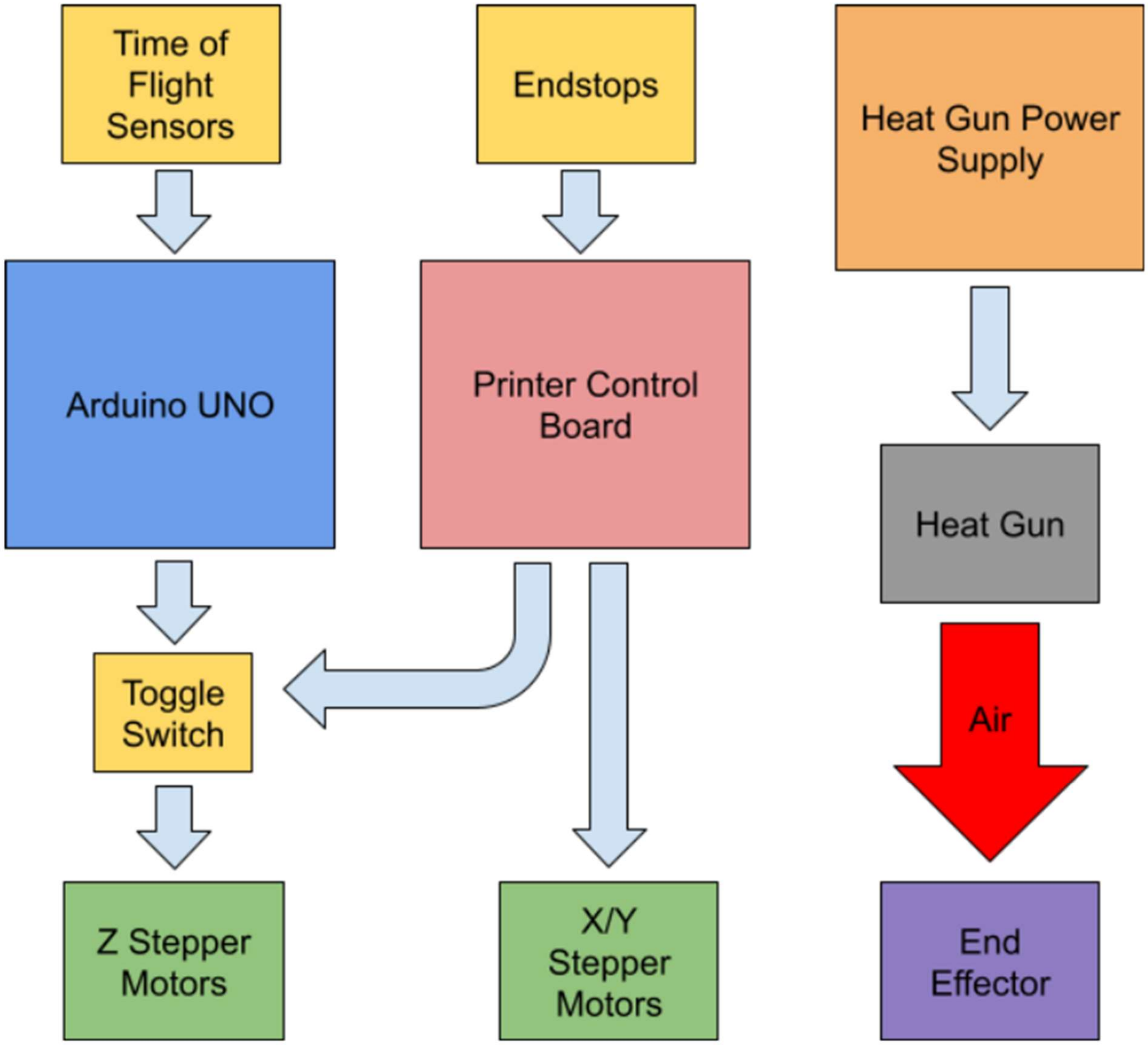

Figure 33. Block diagram of electrical components

The motion system is controlled using the RAMPS 1.4 Platform, an open-source, Arduino-based CNC controller specifically designed for use with FDM 3D printers. Although our system is not an FDM printer, it still contains 4 stepper motor driven axes, so adapting it for use with our silicone system was a trivial task which could be solved with minor firmware modifications.

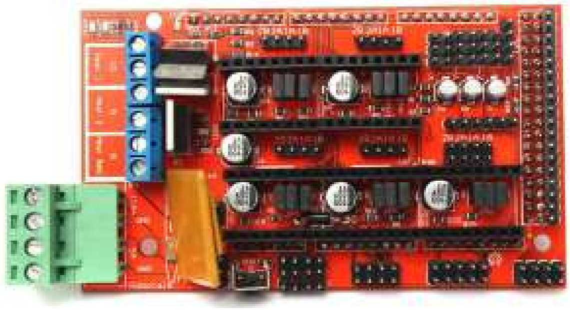

Figure 34. RAMPS 1.4 Board (RepRap World, n.d.)

The three axes of motion have at least one motor and an end stop wired to the control board, and the fourth axis controls the extrusion system with two steppers. These are all wired into the RAMPS board, into their respective stepper drivers. A full system diagram can be seen below in *Figure 35*.

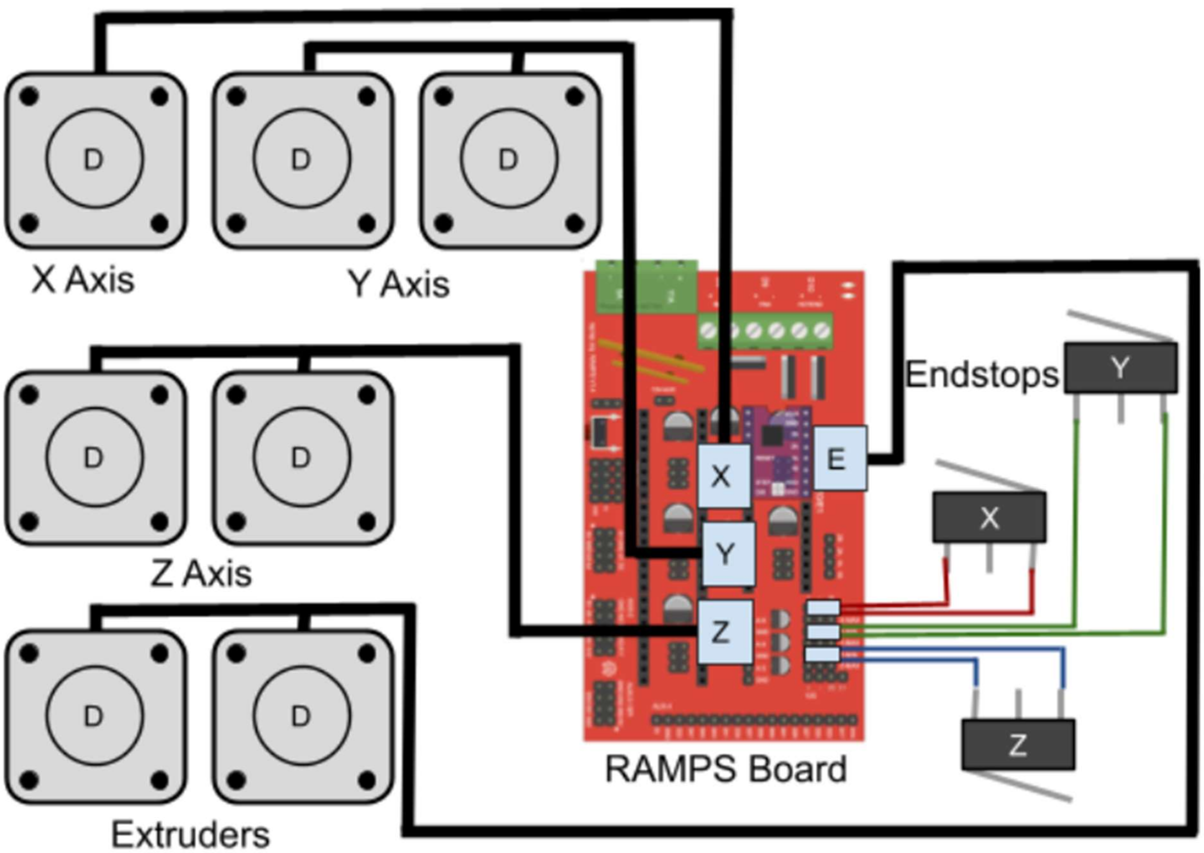

Figure 35. Motion system electronics

The RAMPS board runs an open-source firmware called Marlin. This operating system, coded in the C++ programming language, is responsible for converting a list of g-code commands from a slicer into power signals from the control board which drive the stepper motors and read the inputs from the end stops. Configuring Marlin was a simple task, involving changing just a few constants in the Configuration.h file of the firmware. These were parameters relating to the bed size of the printer, the overall configuration of the x, y, and z axes, and the end stops.

Additionally, since the heating system is controlled without the use of software, some firmware changes were necessary so that the printer would function without a temperature measurement device and heater installed. Normally, the firmware has safety features which disable the motors if the heat is not on or detected, but these were disabled. Since the printer has no thermistor, a dummy thermistor value was enabled, so that the firmware and host software would not perform any safety checks prior to moving any axis of the printer.

For the slicer, cura was an obvious choice, as it allows customization for a vast array of print settings, and some team members were already familiar with the software, from prior experience with FDM 3D printers. By default, cura is configured for use with FDM printers, so finding the correct settings to work with a system such as the silicone printer is a tedious process.

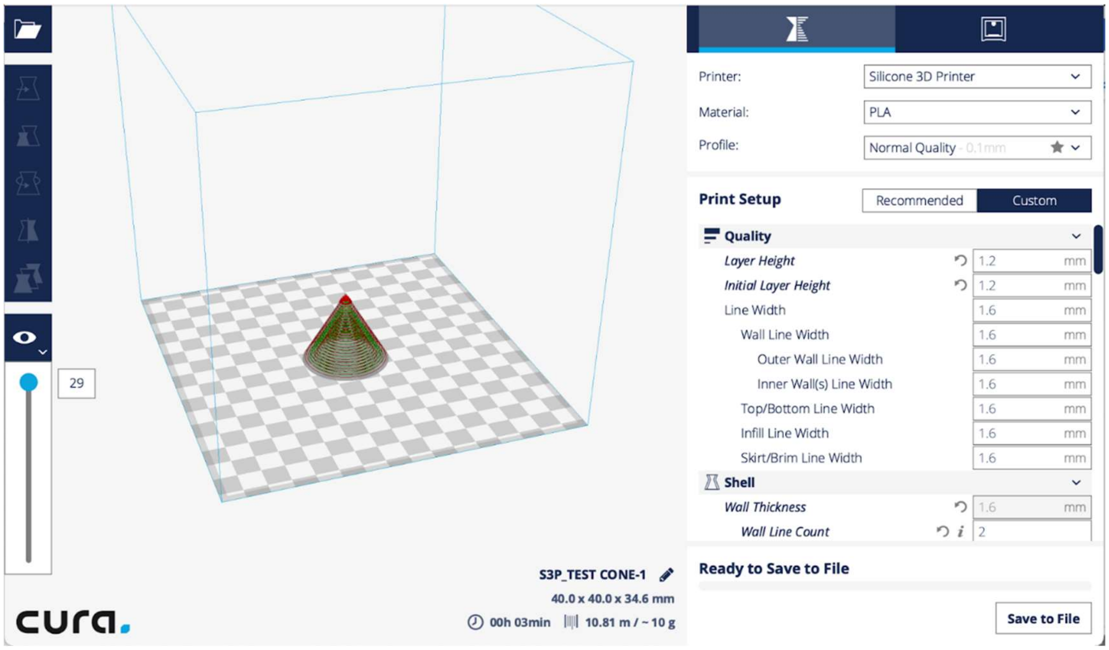

Figure 36. Cura Slicer Interface showing settings for a test cone shape

The above figure shows the slicer settings that were used for a test print of a hollow cone. This shape was chosen for its ability to demonstrate the printer's ability to print circular shapes with overhangs, as might often be needed for devices such as speaker diaphragms.

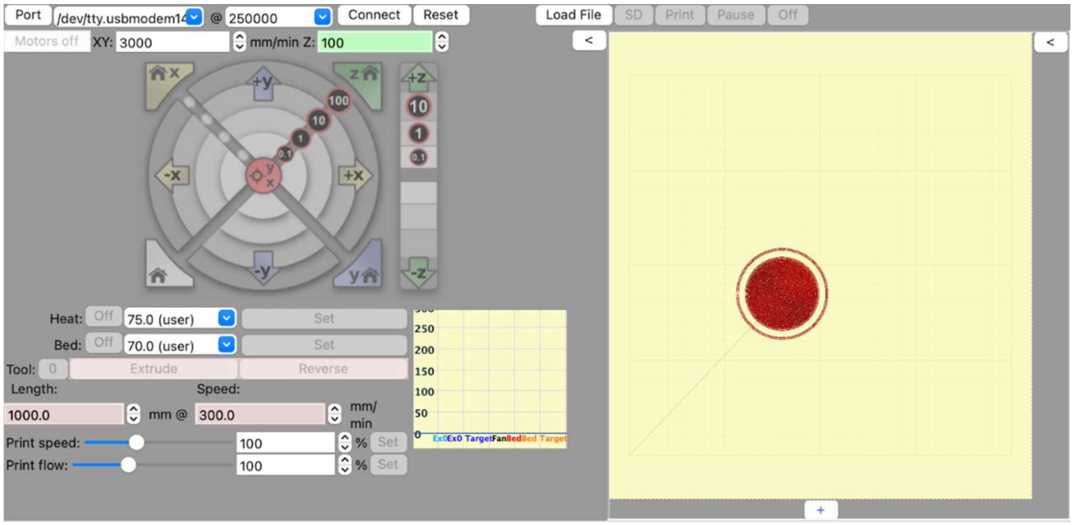

Figure 37. Pronterface host software interface

3.4. Bed Leveler

The bed leveling system was created from scratch to give the team a chance to think outside of the box instead of using a prebuilt sensor system. Not only did it give the team a challenge, but it also allowed for the sensor casings and hardware to be specifically designed to fit the printer with precision. The Flat Bed Leveler - or FBL - was created with two laser time of flight (TOF) sensors pointing down from the top of the printer to two opposing halves of the printer bed. The design for these sensors was designed to fit on the motor housing on each of the two z-axis motors as shown in *Figure 38*. This was designed to level about the x-axis assuming that the built-in rigid bar underneath the bed would inhibit rotation about the y-axis. The two TOF sensors were wired onto an l293d motor driver shield which was attached to an Arduino Uno microcontroller board. The casing for the Arduino/microcontroller duo with the LEDs is depicted in *Figure 39*. The motor driver was connected to a four-pull switch which allowed the power and control of one of two the z axis motors to transfer from the printer microcontroller to the Arduino Uno of the FBL. LEDs were used with the microcontroller to mark when the bed is leveled about the x-axis. The wiring diagram for the FBL is depicted in *Figure 40*.

The motor driver is instructed to move in step increments to go up or down depending on which of the TOF sensors had a distance reading closer to the bed of the printer. Coding two of the same TOF sensors proved to be difficult and time consuming, assigning matrices and different pin layouts to split analog pins on the very limited l293d motor shield pin setup. I2C was a vital part in wiring and coding these sensors. The sensor matrices and motor were defined at the beginning of the code and the rest of the code called on the m accordingly. The code created is shown and detailed step by step in Appendix B.

Figure 38. Evolution of the vl53loz TOF sensor casing

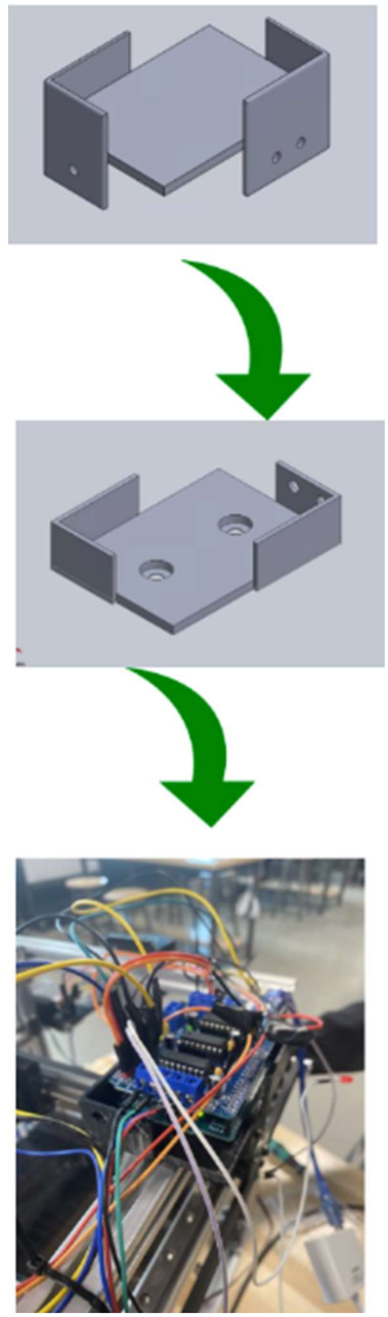

Figure 39. Evolution of the Arduino and l293d shield casing.

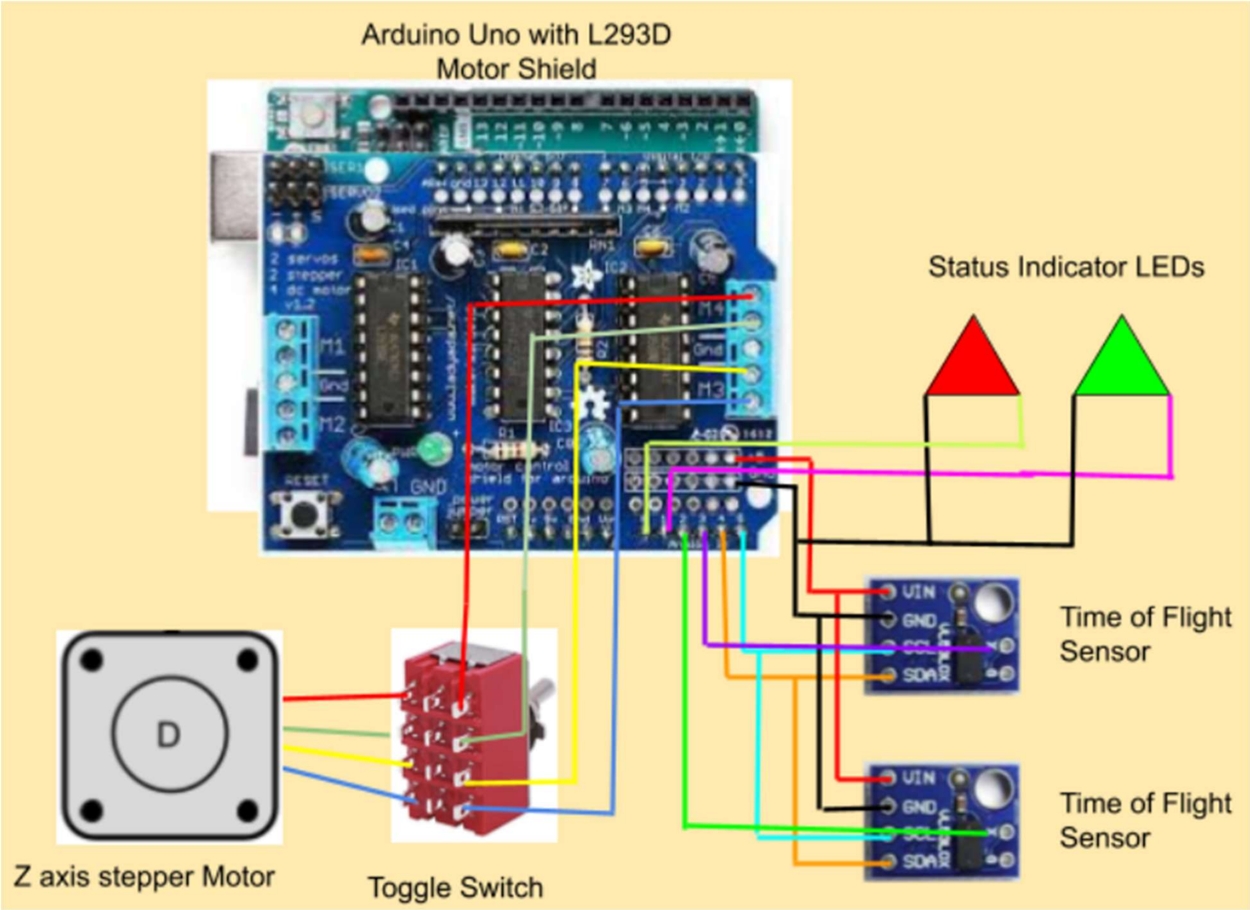

Figure 40. Bed Leveler wiring diagram

4. Results and Analysis

Once the prototype was fully assembled, the next task was to determine the optimal print settings with which to print. For a test print, the team designed a hollow cone 3D object in SolidWorks, which was able to demonstrate several desired qualities of the prints. These included the ability to print thin cross sections in the x/y plane, the ability to print overhangs, and the ability to print structures with significant height unsupported.

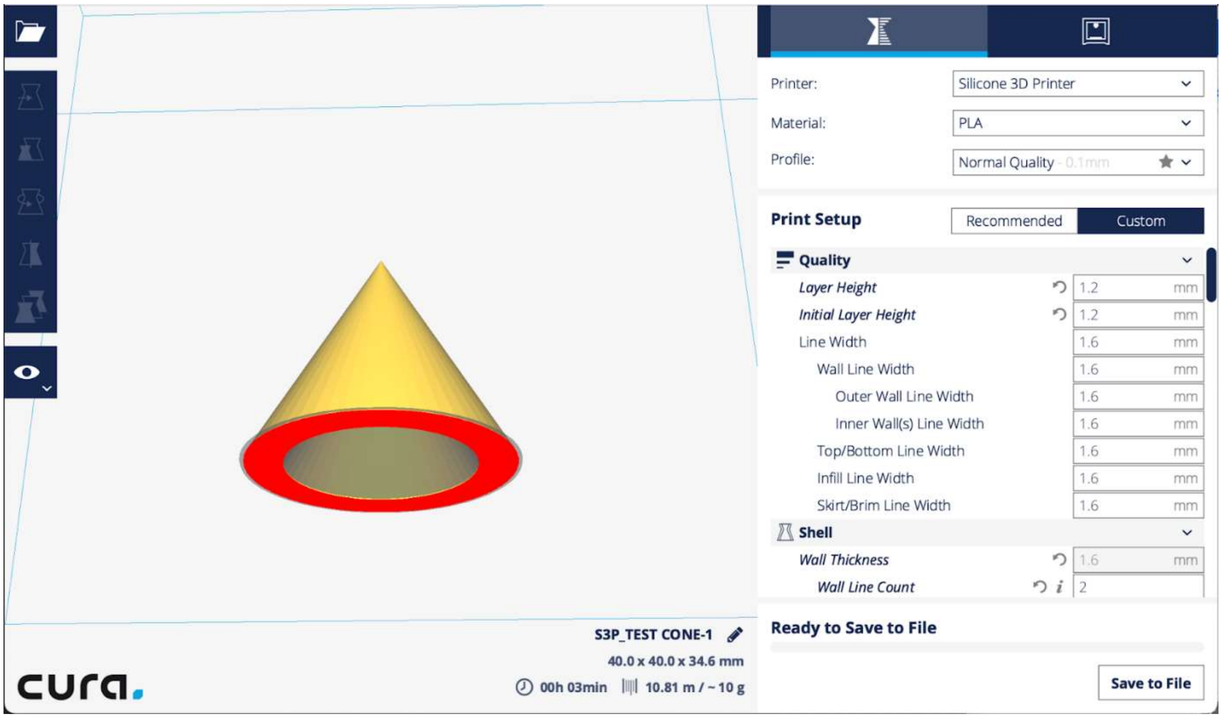

Figure 41. Cura Slicer Interface with hollow cone model

The team tested printing this conic structure several times, changing only the parameters of layer height and nozzle diameter directly in the slicer settings. Then, during the prints in real time, the values for extrusion rate and print speed were adjusted based on observations made during the printing process. *Table 1* below breaks down the various values for the process parameters that were used.

Table 1. Initial test results

Test	Print Speed (% of full)	Extrusion Rate (% of full)	Nozzle Size (mm)	Layer Height (mm)	Quality Rank (1 = best, 4 = worst)
1	100	50	1.6	0.6	4
2	30	30	0.8	0.6	3
3	20	12	1.6	1.2	5
4	20	12	0.8	1.2	2
5	15	12	0.8	1.2	1

Unfortunately, the printer was never able to print the entire cone. While the team was able to tune the settings for the first few layers, once the printer started on the non-solid infill layers the printer was unable to maintain the same quality. This was due to an increase in speed for these layers, which can be accounted for; the slicer by default has these layers move much faster, and the extruder and curing system were not able to accurately maintain the print quality at the faster speed. This resulted in stringing and oozing, which made the print quality inconsistent and inaccurate. With more testing, these problems would be quite simple to address by making changes in the slicer settings.

Figure 42. Test prints of a hollow cone
Top Row (from left to right): prints 1, 2, 3. Bottom row (left to right): prints 4, 5.

While these printing results are obviously not perfect, they are promising. The heating system was able to cure the liquid silicone in about 15 seconds per layer, much faster than the advertised 30 minutes. When cured properly, the silicone layers adhered to each other to form a homogenous component, and the team was confident that the boundaries between layers would not cause significant stress concentrations or points of failure.

5. Conclusions and Recommendations

This project largely met its goals in that it successfully produced a 3D printer capable of printing silicone. However, since the team spent a majority of the project on completing and iterating the hardware of the prototype, the first area of improvement is to spend more time optimizing the print settings via a detailed design of experiments. While the printer currently produces promising print results, they leave much to be desired in terms of consistency and accuracy, featuring blobs, inconsistent extrusion, and inconsistent curing. Given more time, the team would be able to find the perfect print settings to use in terms of the process parameters: movement speed, layer height, infill patterns, and extrusion rate. These could be accomplished by testing one process parameter at a time, until the best results were accomplished. Once one setting is perfect, the process can be repeated with each parameter until prints reach an ideal quality.

If fully optimizing print settings still yields unsatisfactory results, one hardware change could be to add a secondary extruder for support material. This could potentially allow for taller structures and larger overhangs, and even increase dimensional repeatability by controlling the flow of uncured silicone. Implementing this functionality to the current prototype would be simple, as it could consist of a standard FDM extruder and hot end and use more typical 3D printing filaments such as PLA, ABS or even specialty water soluble support material.

Aside from time, the other major limitation of the project was budget. With additional funds, the team could redesign the extruder system to use a positive displacement pump and flow sensors to allow for a fully closed-loop control system. This would replace the current piston-style extruder system but keep the static mixer and curing system. This would eliminate the very limited volume of LSR Material that the pistons can store, enabling larger prints and continuous operation. A positive displacement pump would be necessary as they are able to control flow rate very accurately. Feeding the pump from a tank such that it could be continuously fed would allow for continuous, uninterrupted printing.

With regards to future work, the significant achievement of this project was a solid platform with which both this team and future teams can conduct experiments. While the print quality in its current condition is certainly not ready for production use, the curing system works well and produces promising results in terms of layer adhesion and shape retention. The motor system in its current form works flawlessly, providing an excellent foundation for future projects, whether they decide to use this approach to silicone curing or an entirely different one. The full Standard Operating Procedure for this unit can be found in Appendix C.

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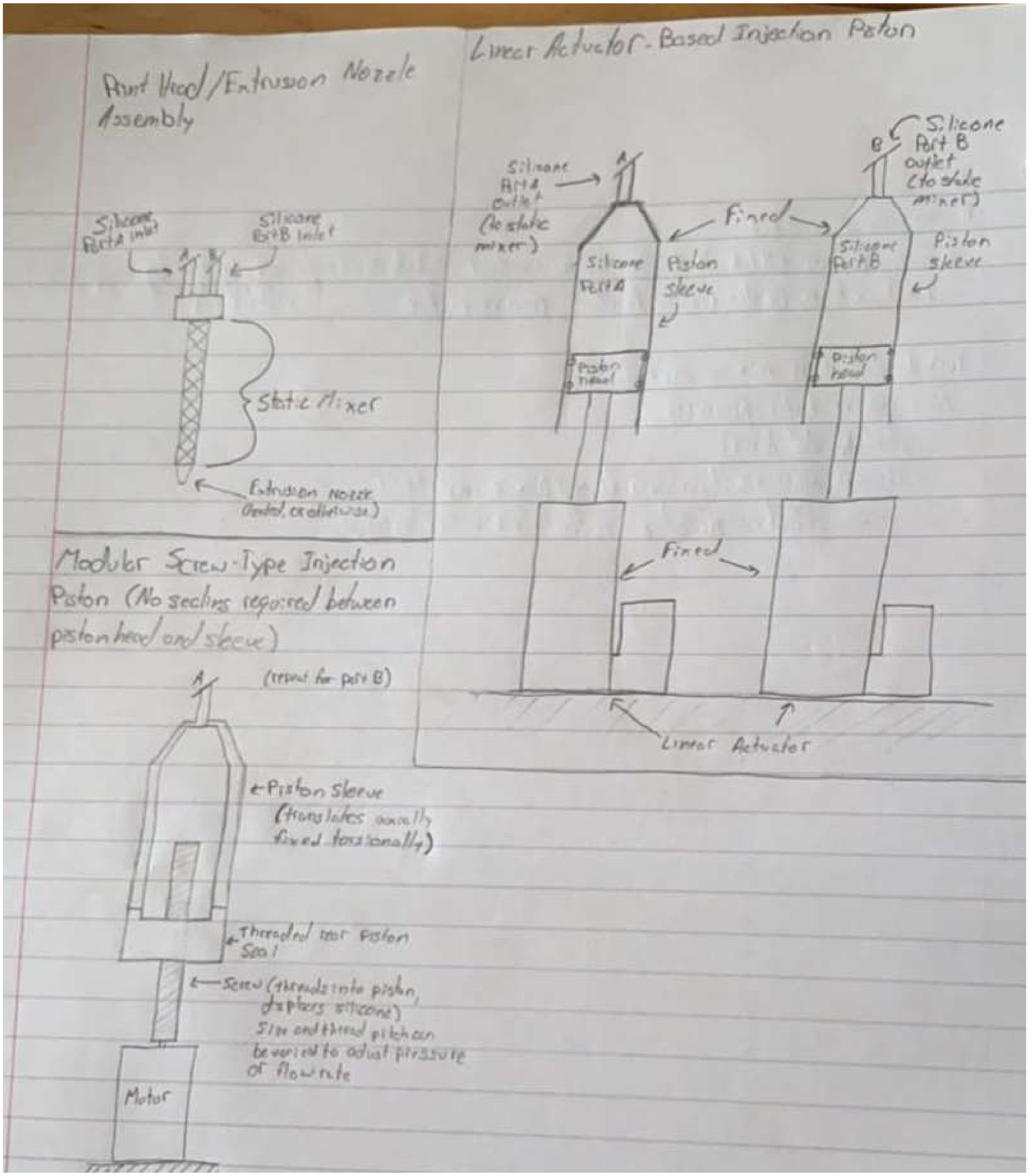
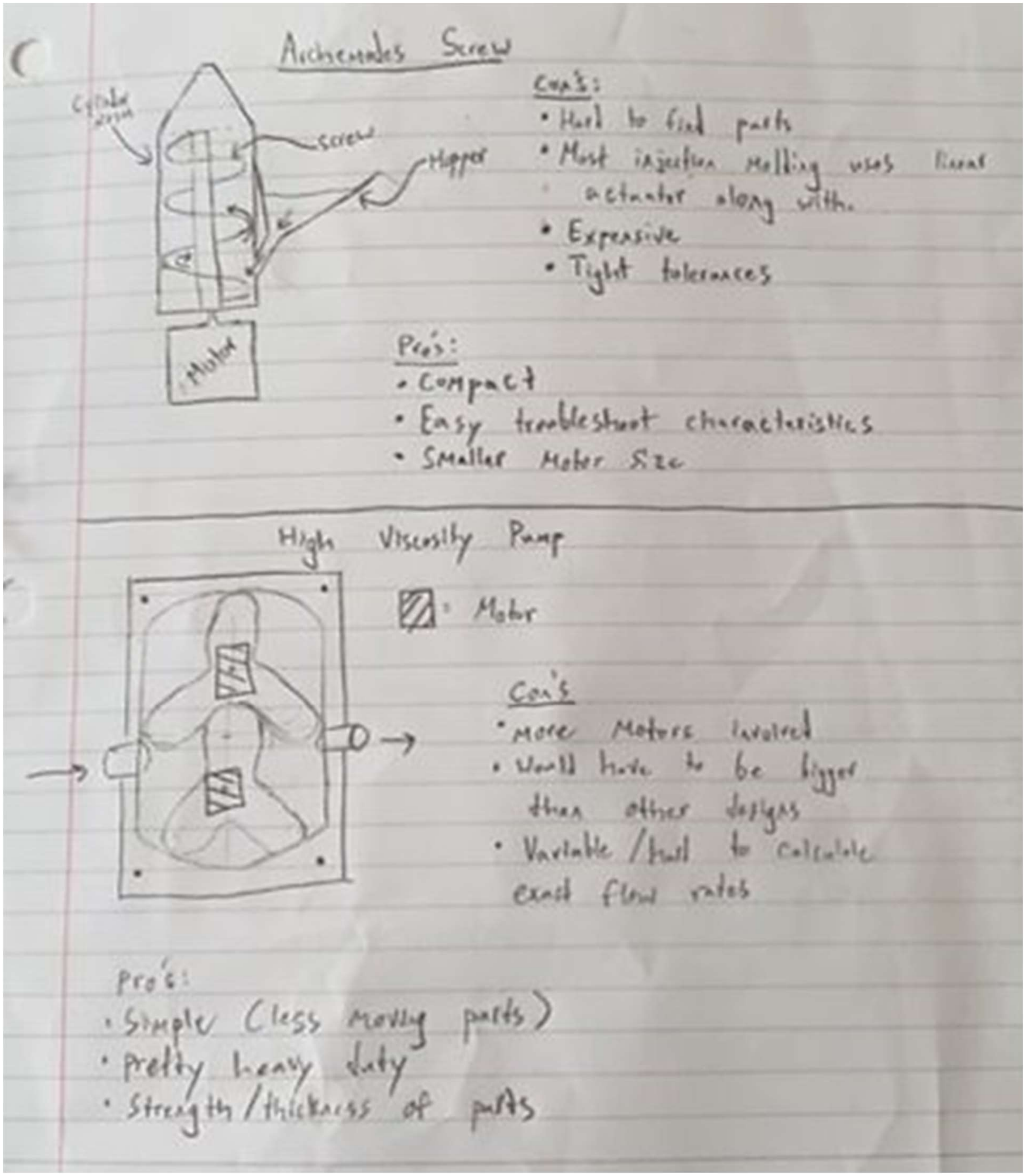
Appendix A: Initial Extruder Sketches




Archemedes Screw
Screw
Hopper
Motor
Con's:
• Hard to find parts
• Most injection molding uses linear actuator along with.
• Expensive
• Tight tolerances
Pro's:
• Compact
• Easy troubleshoot characteristics
• Smaller Motor Size
High Viscosity Pump
= Motor
Con's
• More Motors involved
• Would have to be bigger than other designs
• Variable / hard to calculate exact flow rates
Pro's:
• Simple (less moving parts)
• pretty heavy duty
• Strength / thickness of parts

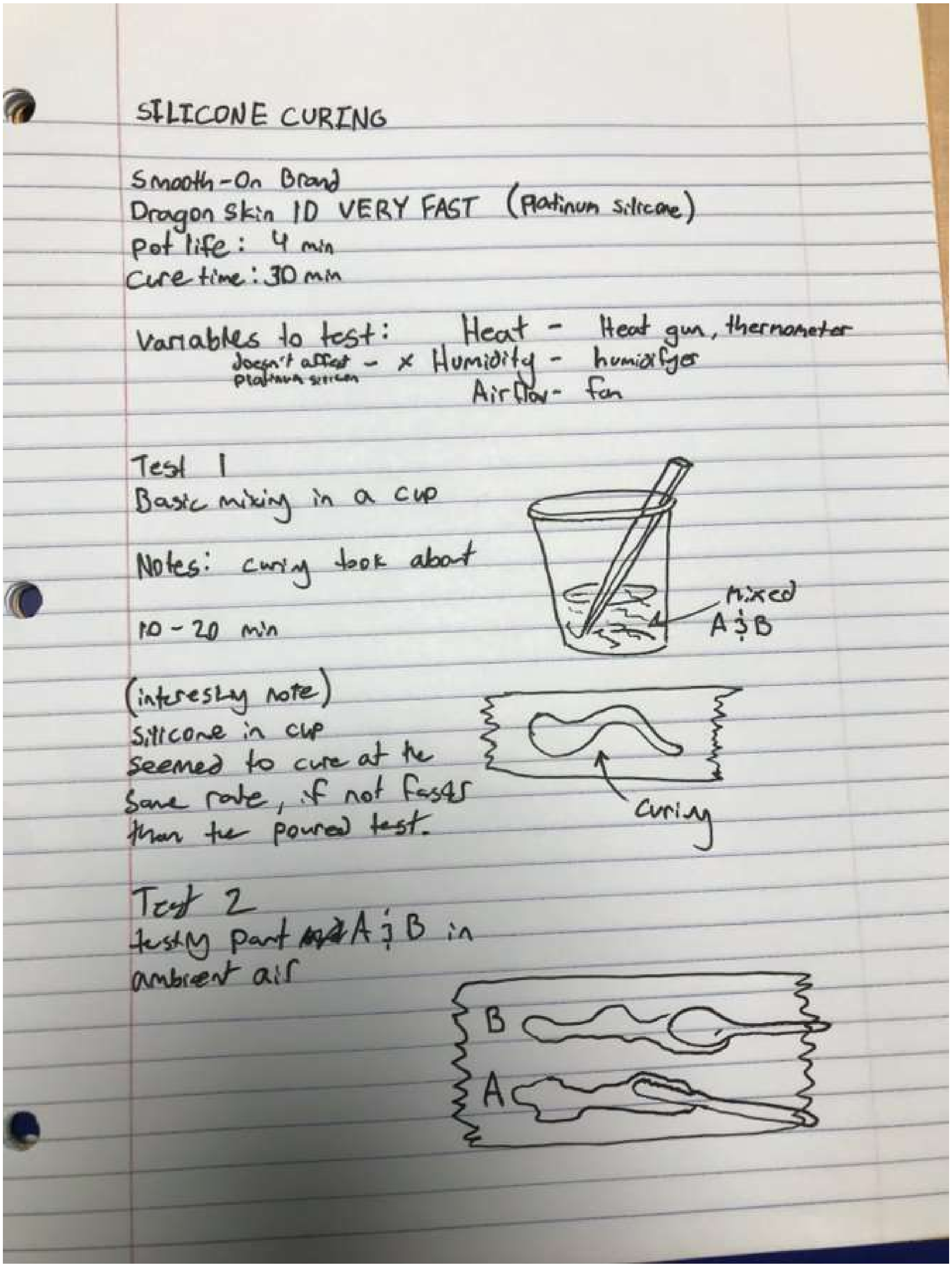
Appendix B: Laser Optic Sensor and 1293D Motor Driver Code

```
//Defining laser optic sensor and motor in l293D motor driver
#include "Adafruit_VL53L0X.h"
#include<AFMotor.h>

//Defining constant variables and timing of stepper motor adjustments
const int stepsPerRevolution = 48;
AF_Stepper motor(stepsPerRevolution, 2);
int ledR = 14;
int ledG = 15;

// Address we will assign if dual sensor is present as a matrix
#define LOX1_ADDRESS 0x30 //First sensor's adress (location)
#define LOX2_ADDRESS 0x31 //Second sensor's adress (location)

// Set the pins to shutdown as two pins
#define SHT_LOX1 16 //First sensor's shutdown pin as digital pin 16
#define SHT_LOX2 17 //Second sensor's shutdown pin as digital pin 17

// objects for the vl53l0x
Adafruit_VL53L0X lox1 = Adafruit_VL53L0X(); //First sensor's object (variable)
Adafruit_VL53L0X lox2 = Adafruit_VL53L0X(); //Second sensor's object (variable)

// this holds the measurement
VL53L0X_RangingMeasurementData_t measure1;
VL53L0X_RangingMeasurementData_t measure2;

void setID() {
  // all reset
  digitalWrite(SHT_LOX1, LOW); //Shutdown first sensor
  digitalWrite(SHT_LOX2, LOW); //Shut down second sensor
  delay(10);

  // all unreset
  digitalWrite(SHT_LOX1, HIGH); //Set/prep first sensor
  digitalWrite(SHT_LOX2, HIGH); //Set/prep second sensor
  delay(10);

  // activating LOX1 and reseting LOX2
  digitalWrite(SHT_LOX1, HIGH); //Set/prep first sensor
  digitalWrite(SHT_LOX2, LOW); //Shut down second sensor

  // initing LOX1 (first laser sensor)
  if(!lox1.begin(LOX1_ADDRESS)) {
    Serial.println(F("Failed to boot first VL53L0X"));
    while(1);
```

```
  }
  delay(10);

  // activating LOX2 (second laser sensor)
  digitalWrite(SHT_LOX2, HIGH); //Set/prep second sensor
  delay(10);

  //initing LOX2 (second laser sensor)
  if(!lox2.begin(LOX2_ADDRESS)) {
    Serial.println(F("Failed to boot second VL53L0X"));
    while(1);
  }
}


//Telling microcontroller to read both sensors simutaneously
void read_dual_sensors() {

  lox1.rangingTest(&measure1, false); // pass in 'true' to get debug data printout!
  lox2.rangingTest(&measure2, false); // pass in 'true' to get debug data printout!

  // print sensor one reading
  Serial.print(F("1: "));
  if(measure1.RangeStatus != 4) {     // if not out of range
    Serial.print(measure1.RangeMilliMeter+11);
  } else {
    Serial.print(F("Out of range"));
  }

  Serial.print(F(" "));

  // print sensor two reading
  Serial.print(F("2: "));
  if(measure2.RangeStatus != 4) {
    Serial.print(measure2.RangeMilliMeter);
  } else {
    Serial.print(F("Out of range"));
  }

  Serial.println();
}


//setting up sensors and microcontroller
void setup() {
```

```
  Serial.begin(115200);
  motor.setSpeed(10); //Setting the speed of the steps of the stepper motor to 10
                      //steps per second

  // wait until serial port opens for native USB devices
  while (! Serial) { delay(1); }

  pinMode(SHT_LOX1, OUTPUT); //Making sensor 1 and output
  pinMode(SHT_LOX2, OUTPUT); //Making sensor 2 and output

  Serial.println(F("Shutdown pins inited..."));

// Shutting down both sensors for reset
  digitalWrite(SHT_LOX1, LOW);
  digitalWrite(SHT_LOX2, LOW);

  Serial.println(F("Both in reset mode...(pins are low)"));


  Serial.println(F("Starting..."));
  setID();

// Make both LEDs an output value
    pinMode(ledR, OUTPUT);
    pinMode(ledG, OUTPUT);

}




void loop() {
  //read both sensors
  read_dual_sensors();

  //each variation is put through an if loop (if one sensor is greater than the other,
  //move the attached motor to adjust until equal
  Serial.print(F(" Leveling: "));

    if (measure1.RangeMilliMeter < measure2.RangeMilliMeter-21){
  Serial.print(F("Down "));  //move motor counter clockwise to raise one side of bed
      motor.step(5, FORWARD, SINGLE);//5 step adjustments clockwise to lower one side of bed
      digitalWrite(ledR, HIGH); // red because not level
      digitalWrite(ledG, LOW);
  }else if  (measure1.RangeMilliMeter > measure2.RangeMilliMeter-19){
  Serial.print(F("Up ")); //move motor counter clockwise to raise one side of bed
      motor.step(5, BACKWARD, SINGLE); //5 step adjustments counter clockwise to raise one side of bed
      digitalWrite(ledR, HIGH); // red because not level
      digitalWrite(ledG, LOW);

 }else if(measure2.RangeMilliMeter-19 <= measure1.RangeMilliMeter <= measure2.RangeMilliMeter-21){
 Serial.print(F("Level "));
     motor.step(0, RELEASE); //stop motor because bed is level
     digitalWrite(ledR, LOW);
     digitalWrite(ledG, HIGH); // green because bed is level
     exit(0); // stops code after level is acheived to avoid noise from the sensors after leveling
       }
```

Appendix C: Silicone Curing Test Notes



SILICONE CURING

Smooth-On Brand
Dragon Skin 10 VERY FAST (Platinum silicone)
Pot life: 4 min
Cure time: 30 min

Variables to test: Heat - Heat gun, thermometer
doesn't affect platinum silicon - x Humidity - humidifyer
Airflow - fan

Test 1
Basic mixing in a cup

Notes: curing took about 10 - 20 min

mixed A & B

(interesting note)
Silicone in cup seemed to cure at the same rate, if not faster than the poured test.

curing

Test 2
testing part A & B in ambient air

B
A

Appendix D: Standard Operating Procedure

Standard Operating Procedures

Assembly and Preliminary Setup

1. Install extruder on the side of the printer. The extruder is slid onto the mounts located by the Z Axis motor from the top until it meets the tabletop.

Properly installed extruder (1)

2. Mount the dual syringe body to the mount located on the end effector.
3. Plug in the two cables coming from the extruder stepper motors.
4. If the insulated tubing for hot air is not connected, connect it to the heat gun.
5. Plug the heat gun cable into the heat gun power supply and plug the power supply into a wall outlet.
6. Plug in the main power supply to a wall outlet.
7. Level the print bed using the bed leveling system (See “Using Bed Leveling System” section for details).

Using Bed Leveling System

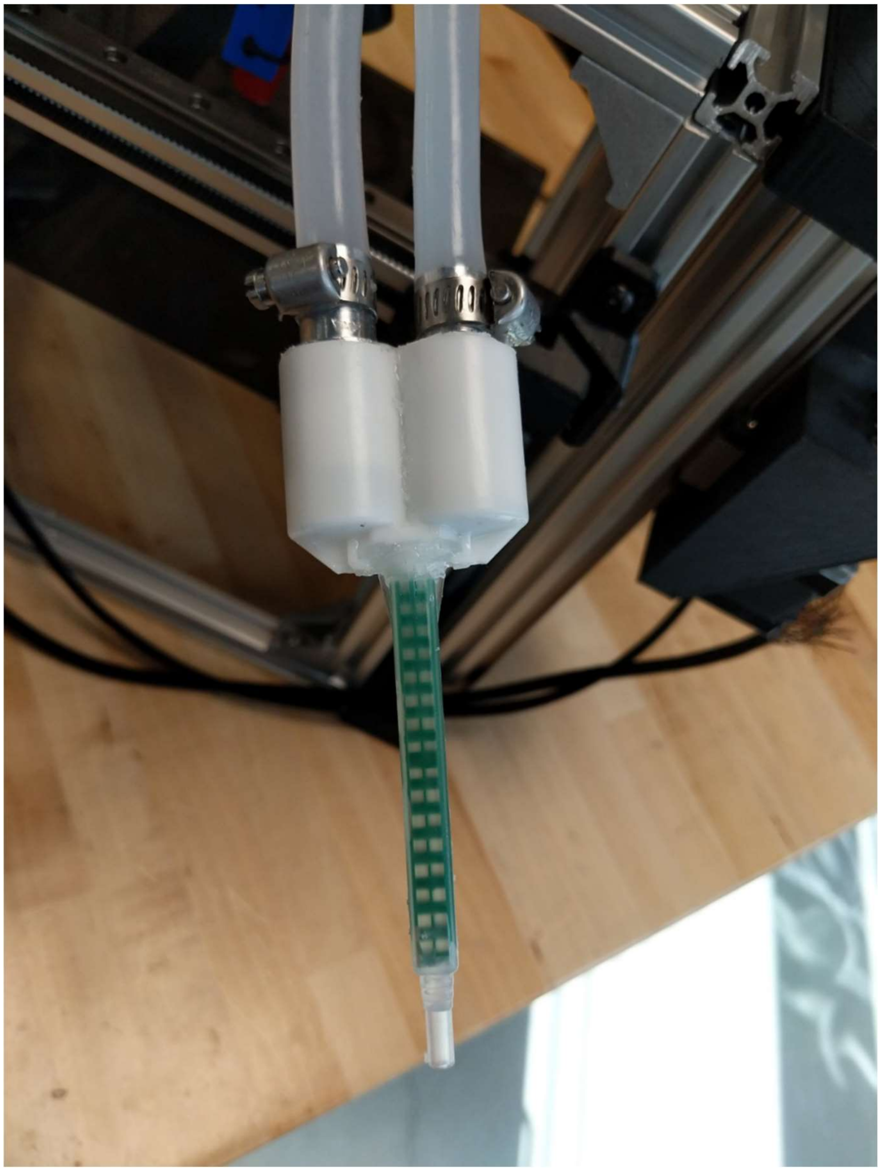
1. Plug in the Arduino Uno into a computer and make sure that the proper code as shown in the Bed Leveling Section is loaded to the microcontroller.
2. Turn the power source on after being plugged into an outlet and make sure that only one of the LEDs are in the ON position.
3. If the GREEN LED is on, then congratulations, the printer's bed is leveled and you can keep the switch in the leftmost position with the power of the motors in full control of the printer’s main microcontroller.
4. If the RED LED is in the on position, then turn the four prong switch to the right most position.

5. Leave on until the RED LED turns off and the GREEN LED turns on. Once the bed is leveled, the motors will automatically stop moving.

6. Restore power to the main printer microcontroller by flipping the switch to the right most position.
7. Have fun :)

Filling the Extruder and Purging Air

1. Ensure that the nozzle is plugged. This can be done either by installing a previously used, and clogged, static mixer to the syringe body (Figure 2 below), or by installing a white syringe body plug (Figure 3 below). This is to ensure that during the following steps, air is not introduced to the system from the end effector end, nor is there backfilling and mixing of silicone parts within the syringe body or tubing.



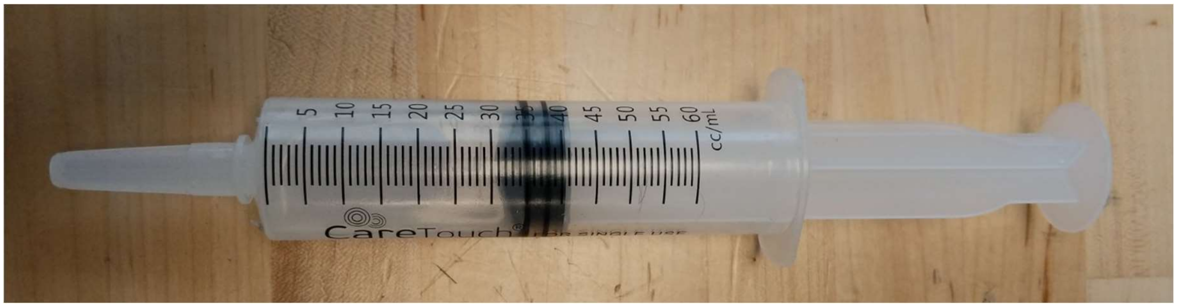
Dual syringe body plugged using clogged static mixer. (2)

Dual syringe body plugged using white plug. (3)

2. Remove the bleed port plug bolts (Figure 4) using an adjustable wrench, thus opening the system.

Bleed Port Plug Bolts (4)

3. With the plug bolts removed, retract the extrusion pistons until they are near the bottom of the piston stroke. The extrusion pistons do not have an end stop, so take care to stop prior to full extension.
4. Fill a clean syringe with Part A silicone. The syringe can be inserted into the Part A bleed port hole and silicone injected into the system. Intermittently remove the syringe or pull on its plunger. This relieves pressure built up in the system and will allow trapped air to escape. Silicone is viscous; therefore air bubbles do not rise quickly, take time with this process as fewer air bubbles will lead to more reliable mixing ratios and therefore more reliable prints. This process can be repeated as many times as necessary to either fill the extruder or to remove a satisfactory number of air bubbles.



Example of a syringe which can be used to refill and bleed the cylinders. (5)

5. Replace the Part A bleed port plug bolt. An adjustable wrench can be used, but it is not necessary to overtighten this bolt. The silicone on the threads will seal the system even without excessive bolt torque.
6. Repeat steps 4 and 5 with a new syringe and the Part B silicone.

Note: It is recommended that the nozzle remains plugged with an old static mixer until ready to print to prevent silicone from dripping due to pressure in the system.

Printing

1. Plug the USB Type B Cable into the RAMPs control board mounted on the front of the printer
2. Pronterface is the recommended host software. With Pronterface open and the printer connected to a PC or laptop, connect to the printer with the "connect" button
3. Now it is time to print. With the printer ready to receive commands from Pronterface, replace the *static mixer* on the printer with a fresh one, free of any cured silicone material. Ensure that both outlets of the white manifold have silicone flowing through them.
4. Attach the *Nozzle* to the end of the static mixer. Make sure that it is clear of cured silicone material.
5. Turn on the heat gun via its power supply
6. Before the silicone cures in the static mixer, start the print. This should be less than 2 minutes after replacing the static mixer. If you need to wait before starting to print, make sure to continuously extrude material so that it does not cure in the static mixer and clog.
7. Click the "print" button in Pronterface to start the Print

Slicer Settings

While the team was not able to fully optimize the slicer settings, the following are the currently recommended settings:

- Layer Height: 1.2mm
- Solid Fill pattern: Concentric
- Infill: 100%
- Line width/Nozzle Diameter: 0.8mm
- Skirt Type: None
- Print Speed: 10 mm/s or less
- Extrusion multiplier: 10-20%

Appendix E: Final Printer Dimensions