Creating a 3D Printer for Liquid Silicone Rubber

by

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Abstract

3D printing, or additive manufacturing, is the creation of a three-dimensional object from a digital 3D model or a CAD model. Additive manufacturing has been applied to countless areas of society such as: manufacturing, aircrafts, automobiles, electronics, robotics, medical, prosthesis, fashion, general commerce, and for educational purposes. The main advantages of 3D printing compared to normal manufacturing processes are in its speed, design flexibility, testability, and cost benefits (MakerBot, 2020). In terms of small production methods, prototyping, small businesses, and educational use, 3D printing is advantageous to other industrial methods. Despite how far additive manufacturing has developed as of today, there are countless opportunities to advance the field such as standardized printing of silicone rubber. Silicone is a polymer frequently used throughout aerospace, textile, automotive and healthcare industries. Silicone's distinct qualities of a high elasticity and the ability to withstand stress and heat makes it a very appealing material for manufacturing. It's bio-compatible regarding medical and sport contexts is also a key feature (SIMTEC, n.d.). An interest in the developing field of 3D printing silicone rubber was identified in the Mechanical department of Worcester Polytechnic Institute by Professor Joe Stabile. A team of students were then tasked to further research the current field of silicone printing along with developing a 3D printer extruder for different varieties of liquid silicone rubber (LSR).

Executive Summary

3D printing, or additive manufacturing, is the creation of a three-dimensional objects from a digital 3D or CAD model. Additive manufacturing has been applied to countless field of study in society such as: manufacturing, automotive, electronics, robotics, medical, fashion, general commerce, and for educational purposes. Despite how far additive manufacturing has developed as of today, there are countless opportunities to advance the field such as standardized printing of silicone rubber. Silicone is a polymer frequently used throughout multiple industries due to its distinct qualities of a high elasticity, material durability, resistances, and its bio compatibility (SIMTEC, n.d.).

Our problem lies in the reason why silicone is so attractive as a 3D printing material, it is difficult to manufacture so 3D printing silicone instead of the typical injection molding would be preferable but comes with many difficulties. It was our goal to research and design a working prototype 3D printer that can print liquid silicone rubber.

As we started researching the feasibility of 3D printing silicone, we had to determine what elements of typical silicone manufacturing and elements of typical Fused Deposition Modelling (FDM) 3D printing we wanted to incorporate together in our own custom printer. We reproduced a similar pressurized syringe system that we found in our research that allowed us to handle the two-part silicone compound we were using in a simple input mechanism. We then combined the impeller mixing found in injection molding with standard material extrusion and heat systems of a FDM printer. We finalized the design with some additive features and specific components we deemed beneficial to the project.

After determining the design and components needed for the project, we begin collecting parts and building the frame of the printer. We were given a dual axis motorized print bed that we secured to large 3D printed structures that functioned as walls for additional mounting. We mounted a stepper motor and linear slide for our extruder to move up and down onto the print bed along with a stepper motor input system with syringes. One of the hardest components to determine was our own custom-made mixing chamber that would allow the two-part silicone compound to flow into a chamber that would have a motorized spinning impeller that would both mix and push the silicone, with the aid of the pressure from the syringes, into the heating system. We purchased typical 3D printer components for the heating and cooling systems of the printer along with the adapting pieces and nozzle. We were given an Arduino mega to use as our motherboard to wire and program our printer. All components of the printer were custom built, provided by our professor or purchased online.

We built our initial frame and had our base components mounted, then continued to replace or iterate certain parts to allow easier usage of the printer. The main component that was constantly changed was the mixing chamber due to its importance and relation to multiple aspects of the printing process. Whenever the input or output systems were changed or improved the mixing chamber had to adapt to the necessary conditions. Along the way we also had issues

with certain parts of the frame that inhibited movement of or access to the printer, so we modified the printer as needed.

While the mechanical hardware was being worked on for the printer, we also needed to work on the electrical side of things in tandem. From the beginning, our printer ran off an Arduino Mega 2560 with a RAMPS 1.4 shield designed to drive the stepper motors and other components for the printer's operation. While the electrical work was stagnant for much of the beginning, the software it ran on was constantly changing as issues needed to be remedied throughout the configuration process. Whenever something is added to the printer, like a new motor or heating element, that needed to be put into the configuration file and then reuploaded to the Arduino. One of the more drastic additions was the replacement of a weaker dc motor for the mixing chamber for a stronger stepper motor which now needed to be driven by the software, which required a large amount of reconfiguration.

Once the initial testing bed was created, the iterative design process then began as well as the start of our testing. This testing started with dropping the silicone using the mixing chamber and observing the resulting consistency. These tests started with a dc motor driven mixing screw, however this resulted in a critical failure of the part, this was the result of poorly mixed silicone causing a blockage, leading to the overflowing of the mixing chamber and up through the motor. Due to the loss of the dc motor, we needed to covert our mixing apparatus to allow for the use of a stepper motor, this motor led to a far more consistent mix of the silicone parts, which gave us a mixture that cured much faster than the previous batches using the weaker dc motor. With this more solidified liquid silicone rubber, we began to push past the drop test into the printing of a line, what followed was more success within the printing of a semi-retentive line. This began to change as we progressed into the 3-dimensional space, attempting to create a wall, but we were unsuccessful as the silicone quickly cured within the nozzle. This was due to the increases in mixing screw speed, creating a more viscous and rapidly curing material that it would not print for more than 1 inch at the temperature we were testing. So, we proceeded to lower the temperature and solely focus on printing the best and longest line which we accomplished with a 2 inch long retentive (slightly solidified) line of silicone with a gel consistency.

After the multiple tests it was made apparent that the printer as it is now could not print our ideal silicone test, and instead printed in a set of different qualities of tests. With further research and modifications such as implementing electronically controlled air pressure regulator or optimizing the stepper motor driving system for the input system would allow for better conditions during testing. Also constraining the print bed to one axis of movement and implementing a more stabilized dual axis system for the extruder movement would allow for a larger printing surface for future tests. However, the more important improvement that needs to be made is reducing the extruder heat element temperature and apply greater external heat to the printed material after leaving the nozzle to mitigate blockage issues. Through iteration after iteration, this printer could help standardize the methods of 3D printing liquid silicone rubber in manufacturing companies, various fields, and academic programs around the world.

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Introduction

The method of creating 3-dimensional solid objects from a computer file is known as additive manufacturing, also known as 3D printing. Printing is an additive method in which a solid object is created by layering material on top of each other. You can choose from a variety of materials, including plastic and metal. The procedure begins with the development of a three-dimensional digital file, such as one created with Computer Aided Design. Using a simple print instruction, the 3D digital file is then sent to a 3D printer for printing.

In terms of preparation time, 3D printing is a much more viable solution than that of injection molding or subtractive production methods. This is because additive manufacturing does not require any molds being created or any tools being sourced for an operation as a 3D printer can quickly turn an STL file into a tangible product. This movement away from tooling and molds ensures that the prototype stage takes very little prep time and allows for future iterations of a prototype to take place in an equal amount of time as no preparation is necessary other than sending the code to the printer.

For rapid prototyping of this kind to take place, a 3D printer must be acquired. With the amount of 3D printers on the market at various price points at this point, accessibility is not a problem and the technology become more prevalent every day. Even with consumer grade printers, the print itself will be more accurate and more precise than that of traditional manufacturing methods when used for the prototyping stage.

One big part of why 3D printing is revolutionary from a design perspective is the ability to take a part that was designed with software and bringing forth a tangible and accurate copy of the part. Having a part in hand allows for the designer to gauge tolerances and find weak points in a more effective way than that of software alone. And being able to create a physical model of the part as shown in Figure 1, in very little time in order to test in the real world is helpful to an immeasurable degree. And if a problem is found, the designer has the ability to fix the problem within CAD and produce another physical model by the next day. Or in the case of a finished product, being able to customize a part for a specific consumer.

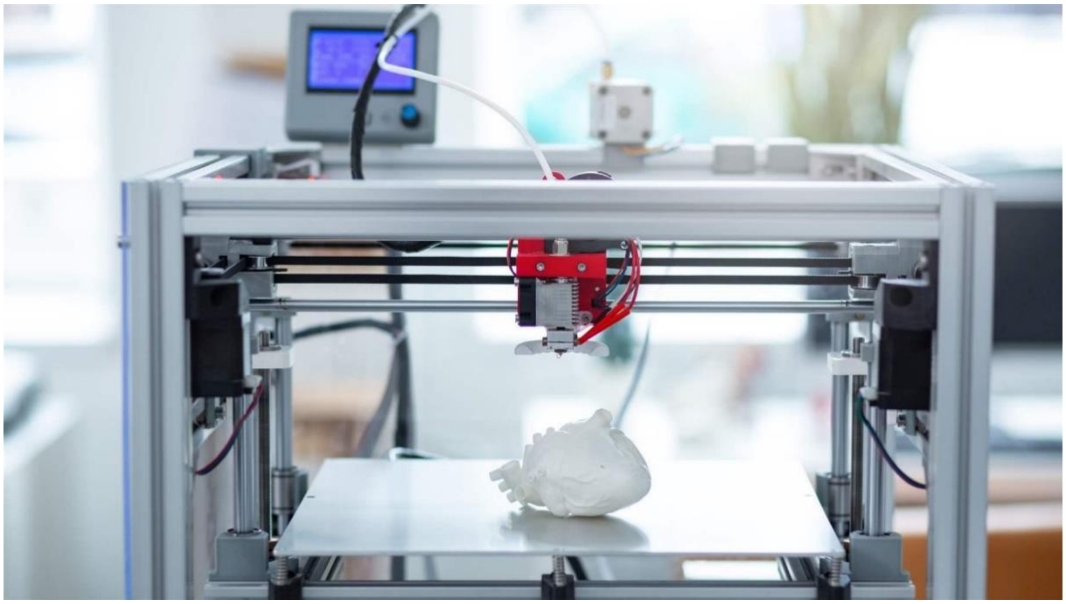

Figure 1: Example of 3D Printing for Medical Applications (Khatami, 2020)

Automation has been pivotal within the reduction of production costs, most importantly when it comes to labor. When using injection molding or subtractive manufacturing, human labor is very much involved in the process. With 3D printing, the human element is all but subtracted from the prototype creation stage, all that is needed to be done is submitting the files necessary to make the part. The printing process is also very straight forward and does not require the same expertise as that of the large-scale production machinery.

3D printing also brings forth a large amount of versatility in comparison to traditional means of production. This versatility comes from the vast variety of geometric shapes in which the only limit to complexity is the amount of support material you want to have. Unlike traditional production methods, raw materials can be directly implemented into the part if you have the correct extruder for the job, something that takes much more planning if done with anything other than additive manufacturing. And with those materials comes minimized waste, as the only material being used is that of the prototype and the occasional amount of support material. This is much less than that of subtractive manufacturing where much of the stock will be removed to create the part, which is sometimes not even reusable in some scenarios.

When it comes to product production, a good designer understands the importance of thorough design verification before investing in a costly molding tool. Material designers may use 3D printing technology to test prototypes before committing to large-scale production investments, which can be costly. You can transform an idea into practice faster with 3D printing than you can with traditional methods. You can transform an idea into reality faster than you can imagine with 3D printing. Products are produced easily and inexpensively. Without a question, technology will continue to change any sector, altering how we operate and live in the future.

Background

History of Additive Manufacturing

In the late 1980s, a man by the name of C.S. Crump invented the additive manufacturing method of Fused Deposition Modelling, otherwise known as FDM. FDM uses the application of a thermoplastic material for each cross section by using a 3-axis robot. Crump would then go on to patent this method and its respective hardware in 1992. This has since become the most accessible additive manufacturing process for consumer grade 3D printers on the market (Sculpteo, n.d.). However, at this time 3D printers are far from accessible and are implemented for the prototyping process within large industries as opposed to the commercially available printers of today and the highly capable additive manufacturing machines used within companies today for final products.

In a push for cheaper and more accessible machines than those found within the industrial prototyping space, a project was carried out at the University of Bath under the lead of Dr. Adrian Bowyer. The printer, named Rep Rap – the replicating rapid prototyper, consisted of a 3-axis robot carrying one or more extruders and used Fused Filament Fabrication, a process derived from the FDM process patented by C.S. Crump (Sculpteo, n.d.). This printer was able to produce a majority of its own parts and was entirely open-source and all electronics were from the Arduino platform, directly addressing the DIY (Do It Yourself) market. This was the first foray into the consumer space for 3D printing and only became more accessible to the public as time progressed. MakerBot Industries, established 2006 in New York City and heavily inspired by the Rep Rap project, began to provide fully encompassing do-it-yourself kits that required very little technical expertise. Originally MakerBot's products started fully open-sourced but transitioned to a closed-sourced platform in its current iterations (Sculpteo, n.d.). The push of open-sourced methods of additive manufacturing spurred public accessibility and heavily reduced the cost to prototype designs.

On the side of industrial application, materials that can be printed have evolved drastically. As machines have been developed for the additive manufacturing of certain metals using either lasers, electron beams, or plasma arcs to heat the metal enough to adhere to the past layer. The most effective examples of this use metal powders and heat the material either through bed melting or laser sintering. 3D printed metal parts are well known for their uniformity and very little tooling required post creation and for the part itself to be customized on an iterative basis with no need for the changing of molds for that desired part to be changed.

Throughout the years, innovators have been able to overcome the difficulty of producing certain materials, but however are currently struggling with a standard for printing silicone. Similar to how metal parts were only created through subtractive manufacturing, producing silicone parts was only possible through injection molding, casting and compression molding.

While there have been significant advances in the field of 3D printing metal parts, printing silicone rubber is still a developing field.

Liquid Silicone Rubber

Liquid silicone rubber is an almost universal material being used from textiles, to prothesis, to automotive parts. Regarding its mechanical properties, liquid silicone rubber has proficient tear and tensile strength, flexibility, elongation, and hardness. This allows the production of parts that can move and alter their form more than typical manufacturing materials. Also, the natural transparency of the material makes it possible to produce custom molded products (Griffin, 2020).

Through extensive testing liquid silicone rubber has demonstrated proficient compatibility with human tissue and body fluids. Unlike other elastomers, liquid silicone rubber is restraint to bacteria growth and will not corrode or alter other materials. The material can also be sterilized through numerous methods and can be adapted to comply with FDA requirements. It is also resistive to water, oxidation and other chemical solutions. Due to its biocompatibility and chemical properties, silicones are widely used in healthcare applications (SIMTEC, n.d.).

Liquid silicone rubber has exceptional insulating properties, offering a substitution for components of electrical applications. Compared to typical insulating material, silicone can perform in exceptionally higher and lower temperatures. It can specifically withstand a wide range of high/low-temperature extremes making it a favorable material in many aspects of automotive and aircraft assembly. Manufactures can even fabricate parts from liquid silicone rubber through injection molding to make them fire retardant allowing them to not melt unlike plastic injection molding methods (SIMTEC, n.d.).

Manufacturing Processes of Silicone Parts

Until recently, the production of silicone parts has been done primarily through injection molding. The injection molding of liquid silicone rubber is comprised of numerous functional and structural factors that designers must address, including: the placement within an assembly, intended use, and the expected loads. More specifically injection molding starts with the uncured liquid silicone in two containers connecting to a pumping system. One container holds the base-forming material, and the other contains a catalyst. A controlled unit automatically releases the two substances at a constant rate, as well as any other additives. The molder can program and customize the molding process including the alignment, pressure, temperature, and other parameters to fit certain specifications (SIMTEC, n.d.).

After the setup, the molding machine (Figure 2) activates all the necessary parameters, and the injection mechanism then pushes the material into the mold and cavities of the machine.

A combination of heat and pressure is applied to the liquid silicone rubber which cures the material until it solidifies. Once completed, the mold opens, the part is removed, and then the mold closes and repeats the process. After the part from the mold, there are often further procedures to be completed such as post-curing, inspection, and packaging (SIMTEC, n.d.).

Figure 2: Powerjet Silicone Injection Molding Machine (Medical, n.d.)

This technology, however, can be very expensive due to the costs of molds making low-volume production cost-prohibitive. Furthermore, if a company decided to change a part design, after producing the set of parts, the mold must be altered, thus adding to the cost and lead time. On the other hand, 3D printing is more flexible since it doesn't require tooling and the cost of the process is not determined by volume. 3D printing silicone is the perfect option when low volumes of parts are needed. Despite the benefits of printing silicone, the field has only recently been developed and due to its high viscosity, silicone is often difficult to 3D print in the same way as other polymers. Also, silicone usually requires elevated temperatures to solidify which is another challenge regarding printing (SIMTEC, n.d.). However, the market for silicone 3D printing is still expanding due the growing demand and innovation in silicone 3D printing technologies.

History of 3D Printing Silicone

Silicone 3D printing is an unfamiliar, but extremely versatile, technology that can be applied in most industries and is currently used in prototyping and low-volume production, allowing companies to produce smaller batches of parts quicker and more economically. The first company to develop technology for 3D printing pure silicone is ACEO, a division of the German chemical giant Wacker Chemie AG. "The process starts by depositing droplets of the material in the shape of a single part layer, which is then cured with UV light. The next layer of silicone droplets is then applied, and the UV light bonds it to the previous one. The process is repeated until the object is complete". The ACEO 3D printing process can be seen in Figure 3 below. Along with having the capability to produce one hundred percent silicone parts, ACEO's process also creates isotropic parts similar to injection molding. This process was also developed to produce parts with different colors and properties, up to four different silicon materials at the same time. This technology is in high demand in multiple industries such as industrial goods, chemical, and medical industries (AMFG, 2018).

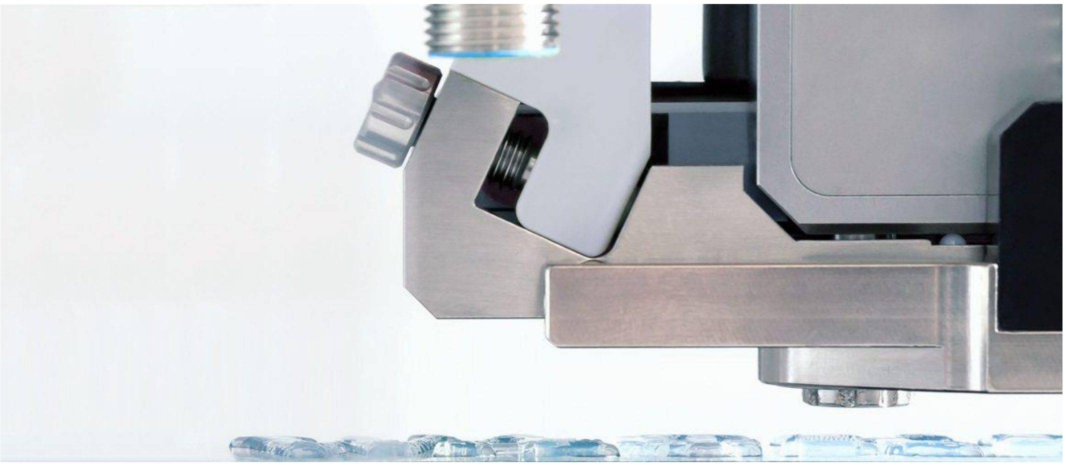

Figure 3: ACEO 3D Printing Process (Essop, 2020)

Other companies such as Henkel and Spectroplast have developed 3D printers based on Digital Light Processing (DLP) technology and are fairly active in the field of silicone 3D printing. Digital Light Processing consists of liquid photopolymer resin curing under a light source and is debated to yield a much greater resolution, improved surface finish, and print time compared to conventional 3D printing methods for silicone. These companies are also developing distinct technologies to further advance the field through an open material platform or new and modified silicone materials (AMFG, 2018).

Another interesting silicone 3D printing technology has been developed by German RepRap. The company is known for its extrusion-based 3D printers, but its silicone 3D printing technology takes a different approach. The method, dubbed Liquid Additive Manufacturing (LAM) by German RepRap, uses liquified polymers, such as silicones, that are deposited layer-by-layer. Unlike Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM), LAM uses liquid material consisting of two components that are mixed in the printhead using precise metering and ideal mixing ratios. Once the liquid is deposited, it gets vulcanized into a solid object through exposure to a heat lamp that passes over the bed between layers as shown in Figure 4. The vulcanization process is said to give LAM 3D-printed parts properties similar to injection molded parts. The LAM process, as well as the first production-ready LAM 3D printer, the L280, were first introduced at Formnext 2018. Recently, the company released a new L320 LAM 3D printer as part of its efforts to further refine the technology for industrial use. It’s also worth mentioning that German RepRap was recently acquired by Arburg, a computer manufacturing company that also produces 3D printers. The effect of the acquisition on the LAM technology roadmap will be important to watch. There is a possibility that Arburg will develop a silicone 3D printer based on LAM, or German RepRap will continue to develop LAM technology under its brand, which is now backed by a large technology conglomerate. Given the increasing demand for 3D-printed silicones and the lack of competition, it’s unlikely that the LAM technology will be phased out (Jackson, 2019).

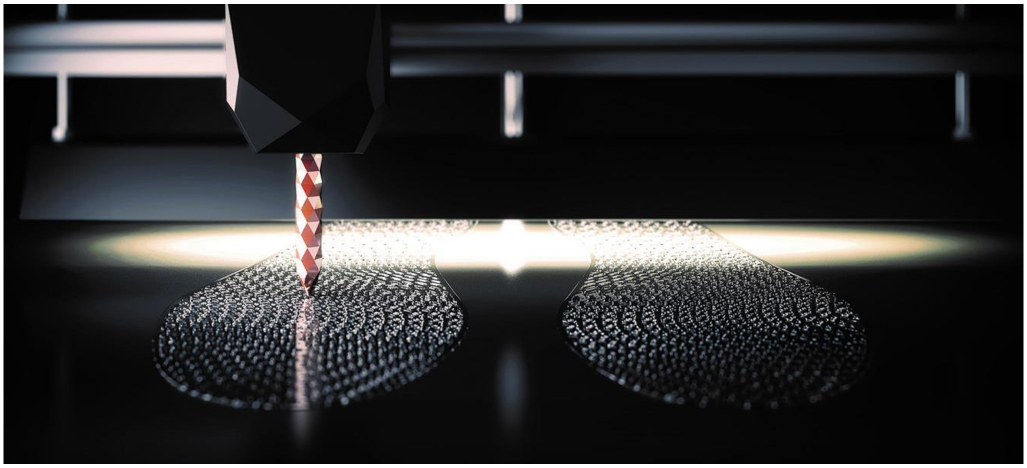

Figure 4: RepRap LAM Technology (Jackson, 2019)

Applications of 3D Printed Silicone

Silicone 3D printing is particularly well suited for applications in the healthcare industry due to its properties such as non-toxicity, biocompatibility, and resistance to UV light and chemicals. Hearing aids, masks, prosthetics, prosthetic liners, tracheal stents and heart valves, as well as orthotic insoles, are examples of these devices. In essence, silicone 3D printing allows for more cost-effective customization of these instruments, resulting in a better match for patients. Silicone 3D printing has been used to create personalized breast prostheses for breast cancer patients, according to one example posted by Spectroplast. In a procedure, known as a mastectomy, ‘part of the breast gets removed and most patients need to opt for an external prosthesis, essentially a silicone object that’s worn in a bra. Today, these come in a few standardized sizes and even fewer standardized shapes and usually don’t fit the anatomy of the patient perfectly’, explains Petar Stefanov (AMFG, 2018). Hospitals can now provide patients with custom-made prostheses that maintain symmetry using the Spectroplast silicone 3D printing service shown in Figure 5.

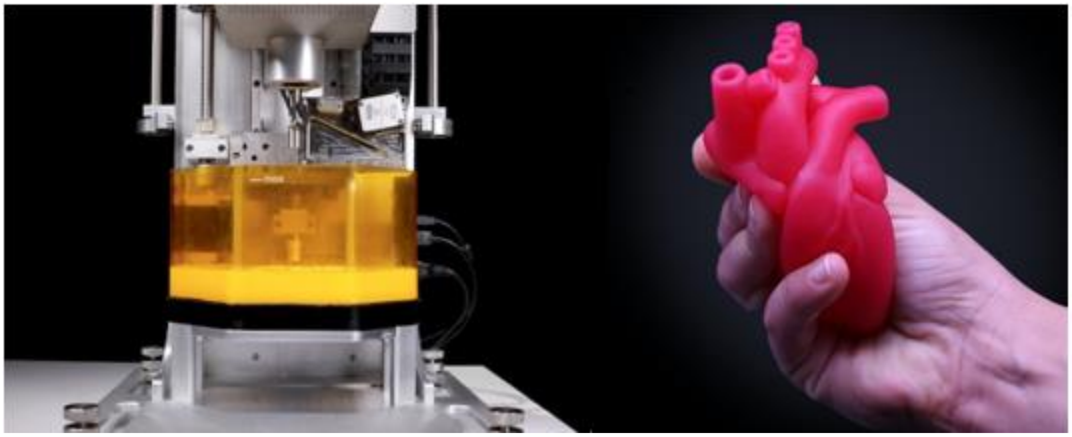

Figure 5: Spectroplast 3D Printing Service and Prints (Stevenson, 2018 - 3d printing, n.d.)

In another instance, Loctite assisted a respirator manufacturer in producing 100 silicone tubes for one of its ventilation products. Because of the design limitations – the tubes were virtually impossible to fabricate due to their very small hollow core – injection molding was not an option. That's why the firm switched to 3D printing, which is known for its ability to produce complex features and data with few constraints. The 100 transparent silicone tubes were 3D printed at a rate of 30 parts per day at a cost of $19 per part, which was substantially less than the $190 per part quoted for injection molding. In addition to cost savings, hard tooling lead times were shortened from four to six weeks to only a few business days (AMFG, 2018).

Silicone 3D printing is used to test and produce soft robotics in the consumer goods industry. Soft robots are made of extremely versatile materials, allowing for modern robot movements that are identical to those of living beings, which are impossible for conventional robots to duplicate. Soft robots are often better at adapting to their environments and are safer around humans. With the aid of silicone 3D printing, a German start-up, Formhand, has created a universal gripper for multi-purpose applications across industries. The team prototyped multiple gripper prototypes using ACEO's silicone 3D printing service. They were able to make customized components easily and at a low cost thanks to the technology (AMFG, 2018).

Silicone 3D printing can be used to make covers for electronic components to shield them from extreme heat, moisture, salt, rust, and dirt, in addition to the applications mentioned above. The technology can also be used to make seals for chemical and automotive applications. Orthodontists use silicone 3D printing to create dental models, which are then used to create a variety of dental products, such as crowns. There are also multiple academic applications for 3D printing silicone, specifically to help manufacturing or mechanical design programs (AMFG, 2018).

Methodology

Throughout the first term of WPI's 2020-2021 academic year, Connor and Johnny researched 3D printing, injection molding, 3D printing of silicone, then determined the needed components to create a 3D printer capable of printing LSR, and finally started designing and printing components for a prototype. From before the start of the academic year, Professor Stabile provided multiple research articles involving various studies of 3D printing along with 3D printing liquid silicone rubber. Connor and Johnny read through the provided articles and both summarizes and noted key aspects of each article. The group also continued researching further into the field through engineering databases to find all applicable knowledge needed to design a 3D printer for silicone. Initially once the term had started the team was finishing the initial period of their researching and delved into brainstorming ideas for the 3D printer that would be adapted from a previous major qualifying project lead by professor stabile. However, after a few weeks of refining the CAD database used for the previous project for the team to us, we decided to focus on specially the extruding mechanism for the time being and then work on the entire printer at a later time.

Designing a 3D Printer and its Features

As we started researching the feasibility of 3D printing silicone, we had to determine what elements of typical silicone manufacturing and elements of typical FDM 3D printing we wanted to incorporate together in our own printer. After numerous meetings, the team decided on certain aspects necessary to build a functional prototype for printing silicone which are: hot end/nozzle, heating system (convective or conductive), pressurized input mechanism, mixing chamber, mixing screw, and a high-speed motor. Examples of the necessary components are shown in Figure 6 below.

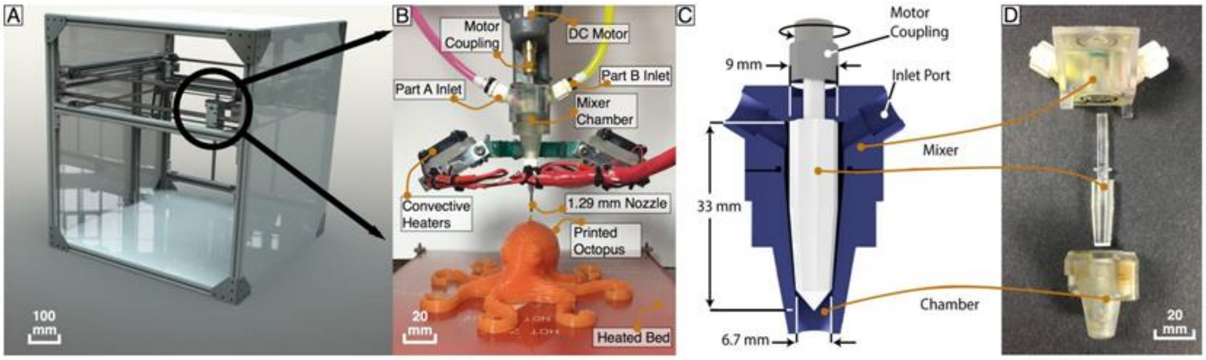

Figure 6: Example 3D Silicone Printer Components (O. D., 2018)

Initial designing of the mixing screw and mixing chamber were the first steps the team took after their ideation process. The mixing screw was initially designed based of the team’s prior knowledge of mixing devices, but the next design was created to replicate the similar function of mixing screws in injection molding. Similar to an auger drilling device the mixing screw has a spiral path along the length of the screw with thin flanges and large openings for material to flow through as shown in Figure 7. The mixing screw was designed to press fit onto the shaft of a small dc motor and spin at a high velocity to mix the base two-part silicone material. The mixing screw and mixing chamber were designed simultaneously due to the dimensioning dependence between the two parts.

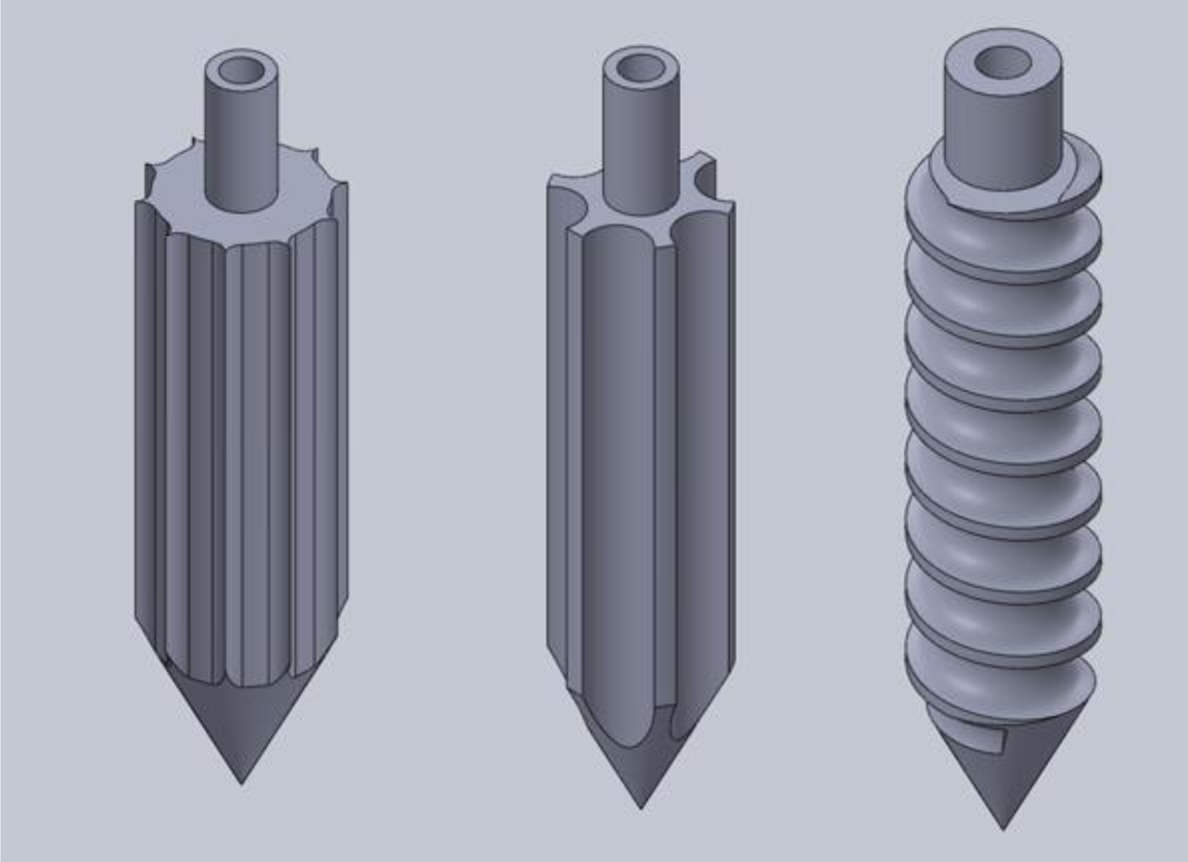

Figure 7: Initial Impeller Mixing Screw Designs

The overall shape and function of the mixing chamber was derived from other successful examples found in the research articles mentioned before. The mixing chamber has a three-dimensional funnel design with the top of the funnel being extruded out for the input system inlet holes and the bottom of the chamber being tapered to adapt to the size of the heating system represented in Figure 8. The mixing chamber was designed into two halves in order for easy disassembly and manipulation of the mixing motor and mixing screw.

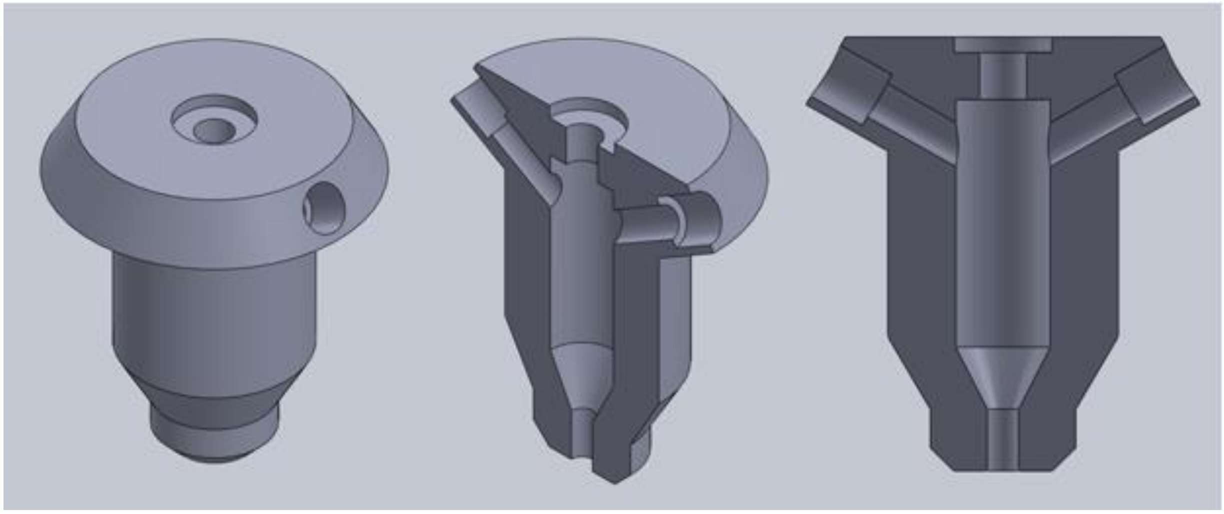

Figure 8: Initial Mixing Chamber Design

For the mixing chamber, the first model went through five iterations, four were optimized to be split vertically and another being optimized for being split horizontally. In order of production, the iterations are as followed: vertical split along the inlet holes without mounting support, horizontal split along the shaft with thin support, vertical split along the inlet holes with thin support, vertical split along the inlet holes with thicker support, and vertical split perpendicular the inlet holes with thicker support. The first iteration was a basic prototype to gauge the necessary dimensions to comply with the parts we had at the time. The next two iterations addressed the issue of securing the halves of the mixing chamber together however in different orientations, one vertically split and one horizontally split as seen in Figure 9 and Figure 10 respectively.

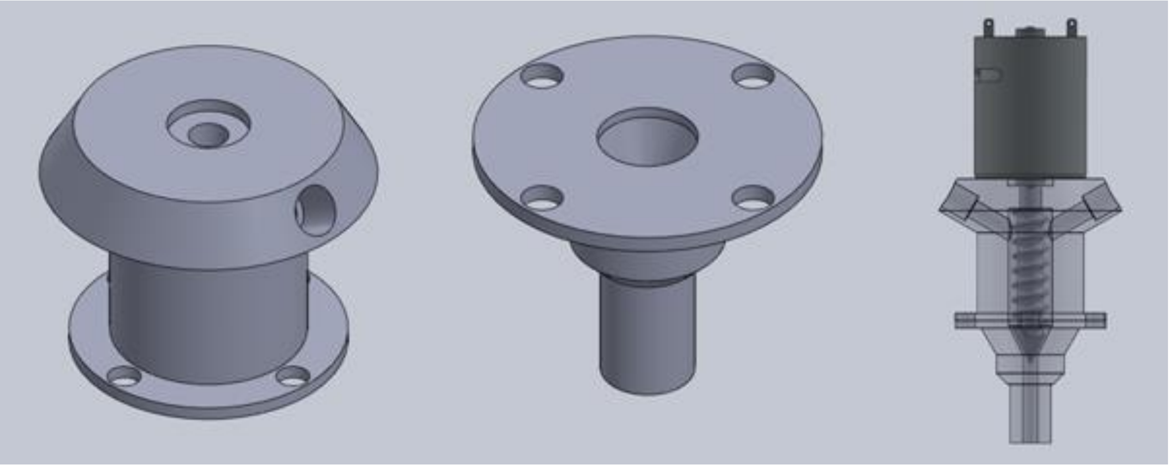

Figure 9: Horizontal Split Mixing Chamber Design

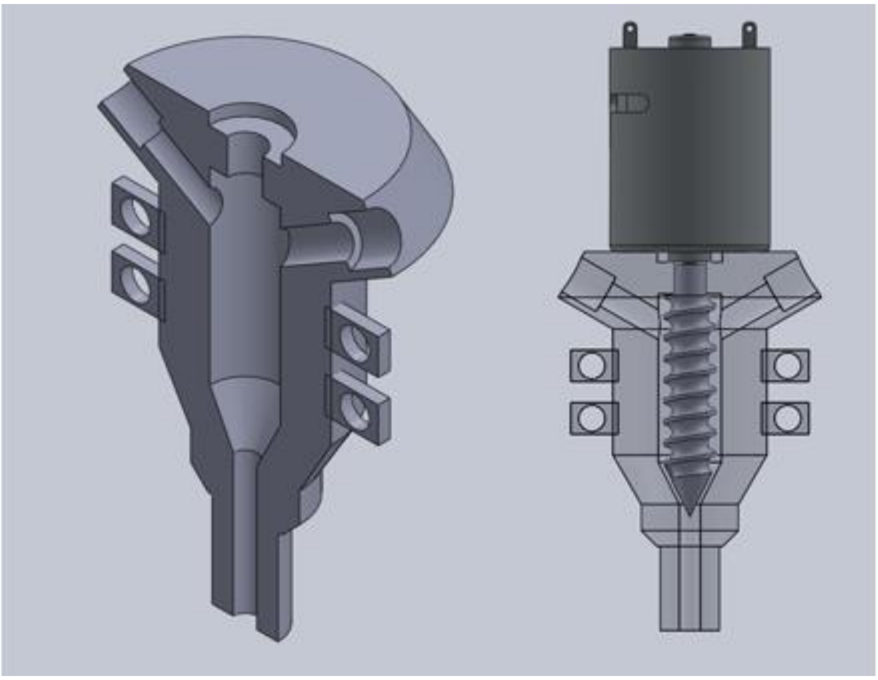

Figure 10: Vertical Split Mixing Chamber Design

We determined that the horizontal split would need further steps to reassemble and test than the vertically split configuration. Both iterations had also been altered to better connect with external parts. The next two iterations had thicker mounting supports since the previous supports were too fragile. Each of these two were also altered again for finer precision of connection between the chamber and the external parts. Both iterations were still split vertically but one iteration however was split perpendicular to the inlet holes so that there would less of a possibility of leakage throughout the system. After reviewing all the iterations, we decided to implement the vertical design with the larger mounting supports. As we finished creating a testable prototype of the extruder mechanism, we also started to design the input mechanism to supply the silicone base and its crosslinker into the mixing chamber.

For an input mechanism, the first idea was a pressure regulator attached to the printer controller, however, this was an overcomplicated design that would also increase the overall expenses of the final product. Instead, two syringes would be used in tandem to be compressed simultaneously via a plate pushed by a lead screw and nut. The lead screw is then powered by a bi-directional stepper motor in order the raise and lower the plate. The syringes being compressed are held in place through indents with identical dimensions to the flanges of the syringe. This holder also features a retaining lip on the outside, in order to remove a spent syringe, the bottom of the flanges must be raised in line with the retaining lip to then be pulled out from either side. This mechanism is to be printed in three parts, the main body, the stepper motor retainer plate, and the articulating lead screw plate. The stepper motor casing is fixed upon the retainer mount using 4 x m-2 screws while the articulating plate is connected to the lead screw nut with 4 x m-2 screws from the bottom. This whole assembly is then lined up within the main body and fixed in place by 4 x ¼"-20 screws on the four corners of the retainer mount.

With the pressure provided by the input system, the two-part silicone is transported into the mixing chamber through the inlet holes and then is mixed by our custom mixing screw. With the downward spiral design of the mixing screw with the pressure form the syringes, the now mixed silicone is pushed through the output of the mixing screw into the heating system. The heating system consists of a heat sink that is screwed onto the end of the mixing chamber that also attaches to a small transfer pipe into an aluminum block that has both a thermistor and a heating resistor. The heating resistor heats the aluminum block to a specific temperature that is determined with the help of the thermistor and regulated through our motherboard. As the silicone passes through the heating block it begins to cure and passes through our custom 1.2 mm nozzle, onto the print bed. Also, in order to assist the curing of the silicone as it is printed onto our print bed, we determined an external heating system would be necessary.

Prototyping Initial System

After determining the design and necessary components for the project we began collecting parts and building the frame of the printer. The mixing chamber and mixing screw were all initially created during the beginning of the project since our first objective was to only design an extrusion mechanism to attach to a 3D printer that would allow it to print LSR. However, it was concluded that it was be the most practical to create an entire custom printer frame for printing LSR along with the extrusion mechanism (mixing chamber & mixing screw). So first we needed to build a print bed for our silicone to print onto, and after some brief designing, we were given a dual axis motorized print bed. This print bed consisted of two stepper motor attached to two perpendicular pieces of 80-20 T-slot aluminum bars, where one set transports the perpendicular set attached above it and attached to the top set is an acrylic print bed as shown in Figure 11. The print bead and one of the stepper motor structure sets move along the rails in the aluminum bars and the custom screws attached to the stepper motor’s shafts.

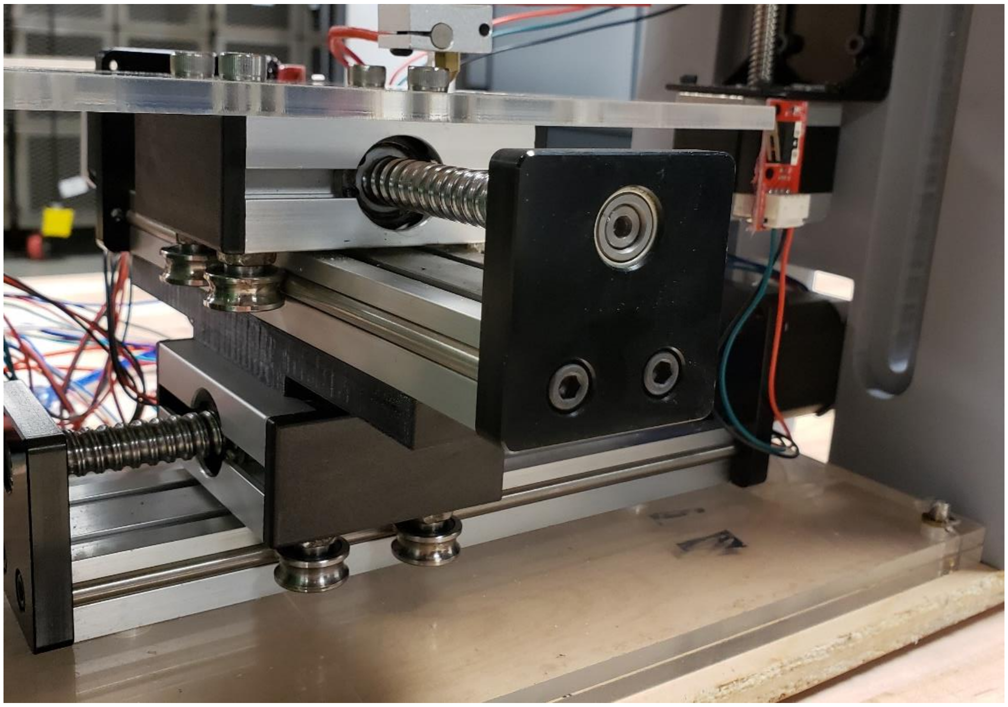

Figure 11: XY Dual Axis Table with Print Bed

The first section of the printer was now complete and then we had to find a solution of how to mount our extrusion mechanism above the print bed. We decided to attach the extruder to a platform that would be raised and lowered onto the print bed with the use of a stepper motor and a provided linear slide. The stepper motor and linear slide necessary for moving our extruder were attached to large 3D printed walls that were given to us by our professor. To attach everything together we attached the print bed and the bottom of the walls onto a piece of plywood in the longest orientation for more structural stability which can be seen in Figure 12. After measuring the distance between the walls of the printer frame we designed a layout for our final platform, which we laser cut out of a piece of plywood and attached it to the mounting side of the linear slide and the brass fitting for the stepper motor screw.

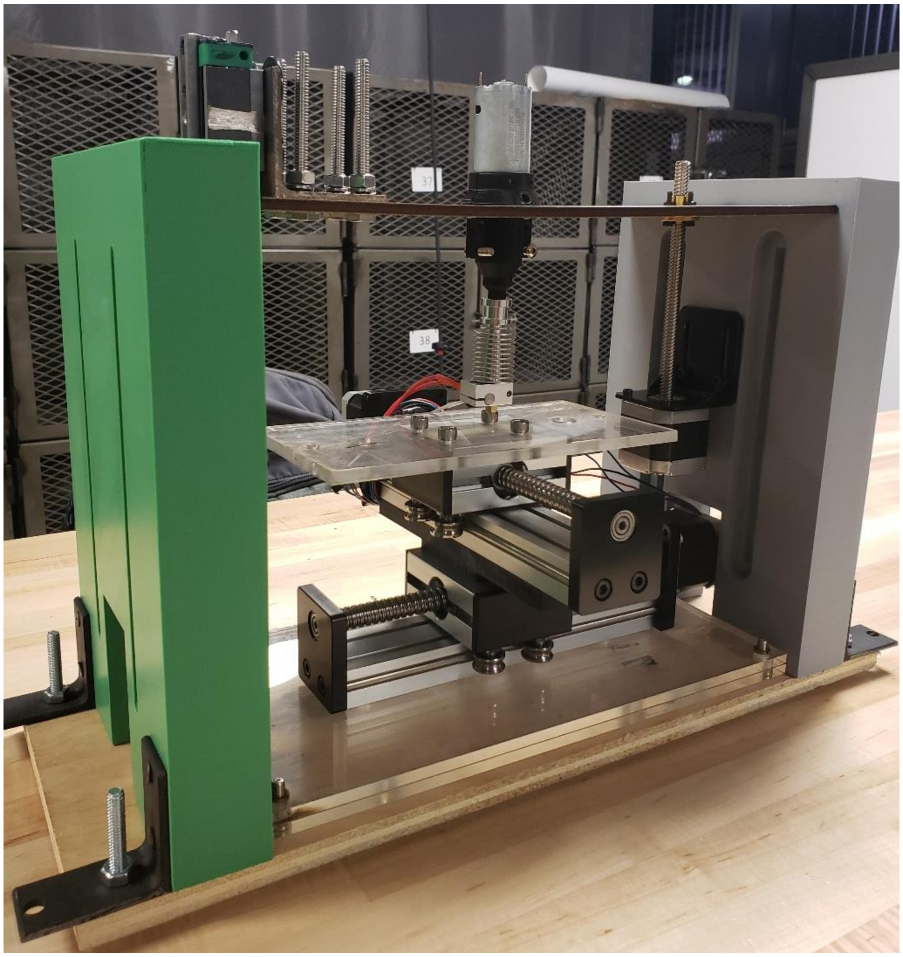

Figure 12: Outer Prototype Printer Frame

Once we completed mounting the walls with the horizontal platforms, we then started to create a layout for our syringe input system. The input system was derived from our research of successful experiments with 3D silicone printers that used medical grade syringes with the implementation of an industrial pressure regulator. Instead of a pressure regulated system we planned to use a stepper motor screw mechanism that would have a horizontal plate attached to it that would raise and push the plunger of the syringes. As the stepper motor moved the screw the syringes would slowly inject any silicone within into the extrusion mechanism. The stepper motor and syringes were then placed into a custom housing that would allow two syringes to slid into slots on either side and have the stepper motor mounted below so that the horizontal plate could reach the bottom of the syringe plungers. Both the housing and input system were then attached to the frame of the printer and can be seen in Appendix A.

With the physical frame assembled we attached the extrusion mechanism onto the moving platform and the started to wire all of the electronics that we were using at the time. We were given an Arduino Mega 2560 coupled with a RAMPS 1.4 3D Printer Control Shield, seen in Figure 13 below, into which we plugged in our: XY axis motor table, Z axis stepper motor, and input syringe stepper motor. Each respective element was plugged into its labelled section (X, Y, Z, and E0) with an A4988 stepper motor driver plugged into each utilized section, positioned for the potentiometer of the driver to face away from the power output terminals labeled D8 through D10, in conjunction with 3 jumpers each underneath to enable 1/16 micro stepping. At the beginning of our electrical work, we bought a single standard FDM 3D printer heating block system, with the heating element connected to D10 and the thermistor connected to the respective input pair closest to the blue output terminals on the left labelled T0. Additionally, our dc motor for the mixing screw was attached to a RioRand dc motor controller that allowed us to adjust the voltage/power of the dc motor with a dial, which in turn controlled the rotational velocity, this controller was connected directly to the power supply unit. All of the initial electronics and the wiring of the printer are shown in Figure 14 below.

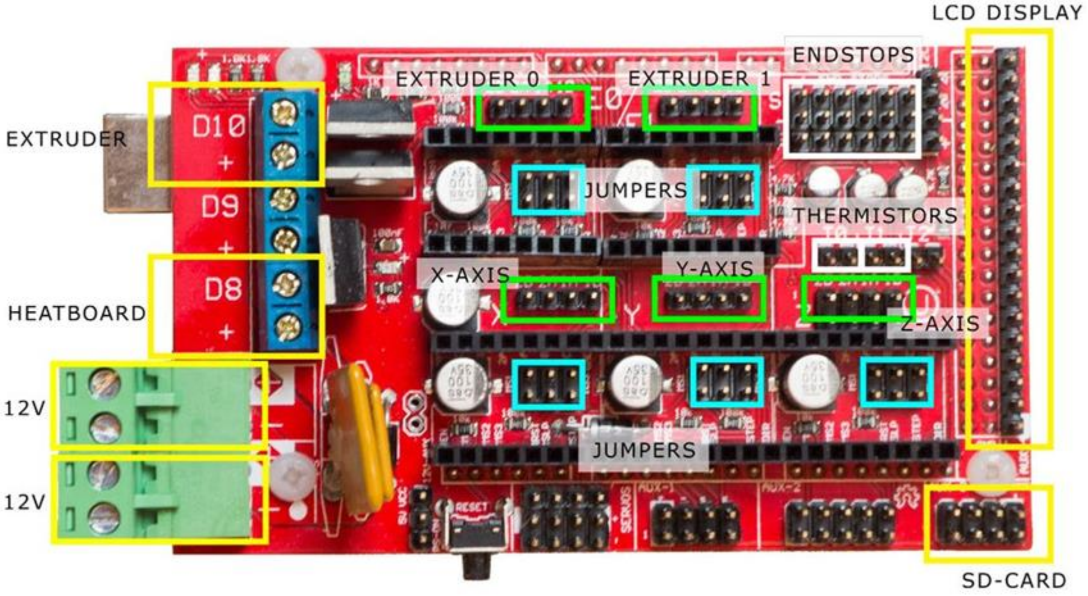

Figure 13: RAMPS 1.4 with Labelled Inputs and Outputs

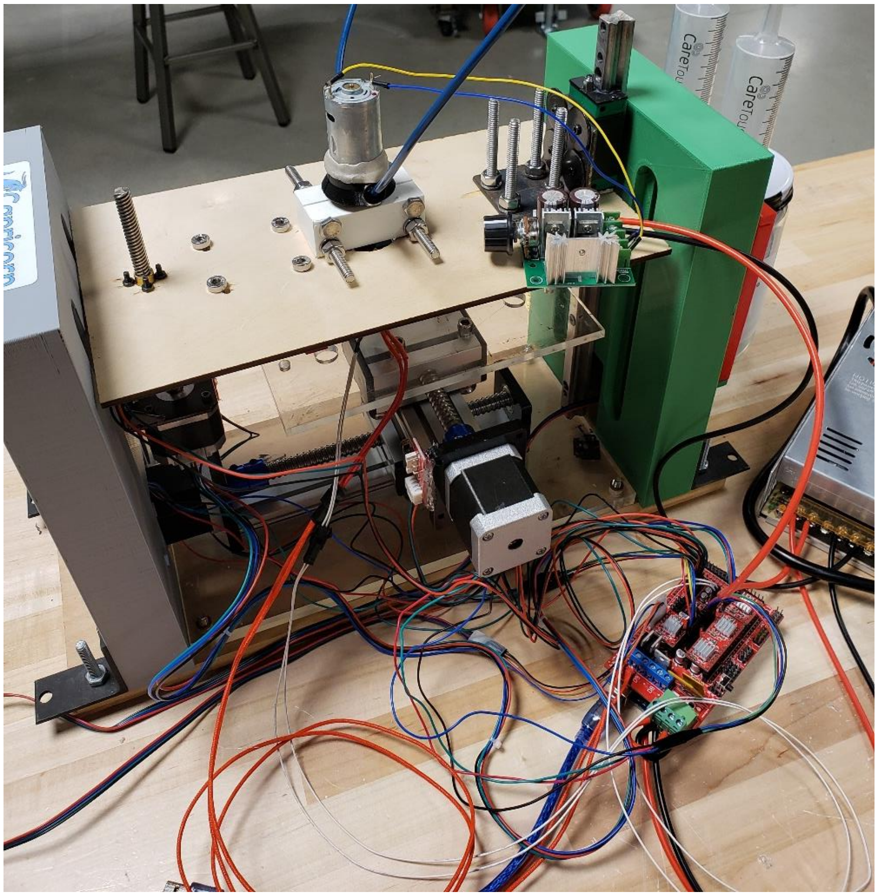

Figure 14: Prototype Printer Initial Electrical Layout

Without the software driving the electronics implemented, very little could be done with the printer. This required us to install Marlin 2.0, an open-source 3D printer software that is popularly used on RepRap based printers and communicates well with the RAMPS 1.4 shield given to us. The installation process required the move from the Arduino integrated development environment, IDE, and onto a more extensive and versatile one. PlatformIO, a Visual Studio Code plugin, was able to successfully load the Marlin software and allow for the extensive configuration necessary to run the printer without any risk of errors.

The configuration process consisted of edits within the *configuration.h* file found within the Marlin 2.0.X folder; a process made significantly easier by the comments left by the creators above each setting indicating how to determine each variable. The first of such alterations to the configuration file was the motherboard variant, this information was found within the *boards.h* file. The RAMPS 1.4 shield used the default configuration, BOARD_RAMPS_14_EFB, which used the three power outputs for the extruder hot end, a cooling fan, and a heated bed. The information found was then used within the *configuration.h* file at the motherboard section to change accordingly:

```
129 | #ifndef MOTHERBOARD
130 |   #define MOTHERBOARD BOARD_RAMPS_14_EFB
131 | #endif
```

Figure 15: Marlin 2.0 configuration.h, Line 129-131.

Once the board type had been selected, the thermistor values near line 70 were changed in order to allow the board to communicate with the 100k beta 3950 1% thermistors used within the selected heat block, the code associated with it being 11, to be used by TEMP_SENSOR_0. This edit to the code can be seen in figure 16.

```
418 | #define TEMP_SENSOR_0 11
419 | #define TEMP_SENSOR_1 0
```

Figure 16:, Marlin 2.0 configuration.h, Line 418-419.

With the thermistor then set up, the next section to configure was the stepper motors, for both direction and steps per unit. One of the stepper motors that required inversion was the motor designated for the syringe pressure regulation system, to invert the signals, in the section located at approximately line 1100 was a Boolean at INVERT_E0_DIR that needed to be converted from false to true. Similarly, the stepper motor in the x direction and z direction need to be inverted, these changes can be seen below in figure 17.

```
1094 | #define INVERT_X_DIR true
1091 | #define INVERT_Y_DIR false
1092 | #define INVERT_Z_DIR true
[…]
1101 | #define INVERT_E0_DIR true
```

Figure 17: Marlin 2.0 configuration.h, Line 1094-1101.

For the steps per unit, the number of steps of the Nema-17 used was 200 steps per rotation with 1/16 micro stepping, which resulted in 3200 steps in total. With the stepper motor rotation transferred into linear motion via a lead screw of 1.25mm pitch, the resulting steps per mm should have been 2560 steps. However, this was not the case and through trial and error the following values were found for the stepper motors to give accurate motion. The code for the steps per unit filled in with the trial and error values can be seen in Figure 18.

```
741 |  * Default Axis Steps Per Unit (steps/mm)
742 |  * Override with M92
743 |  *                                      X, Y, Z, E0 [, E1[, E2...]]
744 |  */
745 | #define DEFAULT_AXIS_STEPS_PER_UNIT { 800, 800, 400, 400 }
```

Figure 18: Marlin 2.0 configuration.h, Line 741-745.

Integrated System Modifications

After we built our initial frame and had our base components mounted, we continued to replace or iterate certain parts to allow easier usage of the printer. The main component that was constantly changed was the mixing chamber due to its importance and relation to multiple aspects of the printing process. Whenever the input or output systems were changed or improved the mixing chamber had to adapt to the necessary conditions. The first major iteration of the mixing chamber was to increase the height of the entire chamber to allow a set of supports to be attached around the primary chamber mounting flanges, that would allow the mixing chamber to be directly secured to the moving platform. Since we 3D printed the mixing chamber, some of the iterations had failed prints that lead us to print new components when it was deemed necessary. To combat the possible failed aspect of the 3D printed parts we also designed two channels that were cut out on one of the halves of the chamber that would contain a rubber material that when attached to the other remaining half, would provide a preemptive seal. When we were first starting to test, we determined that the input tubing and inlet holes were too small with our given situation of having a lack of pressure regulation. We had to change the inlet holes in the mixing chamber to allow silicone to flow through much easier than the beginning of the project. Also, toward the middle of our project we lost the ability to use a dc motor for the mixing screw and had to adjust the motor mounting on the mixing chamber for a small nema-8 stepper motor. Our current model of the mixing chamber can be seen in figure 19 below and all other iterations can be found in Appendix A.

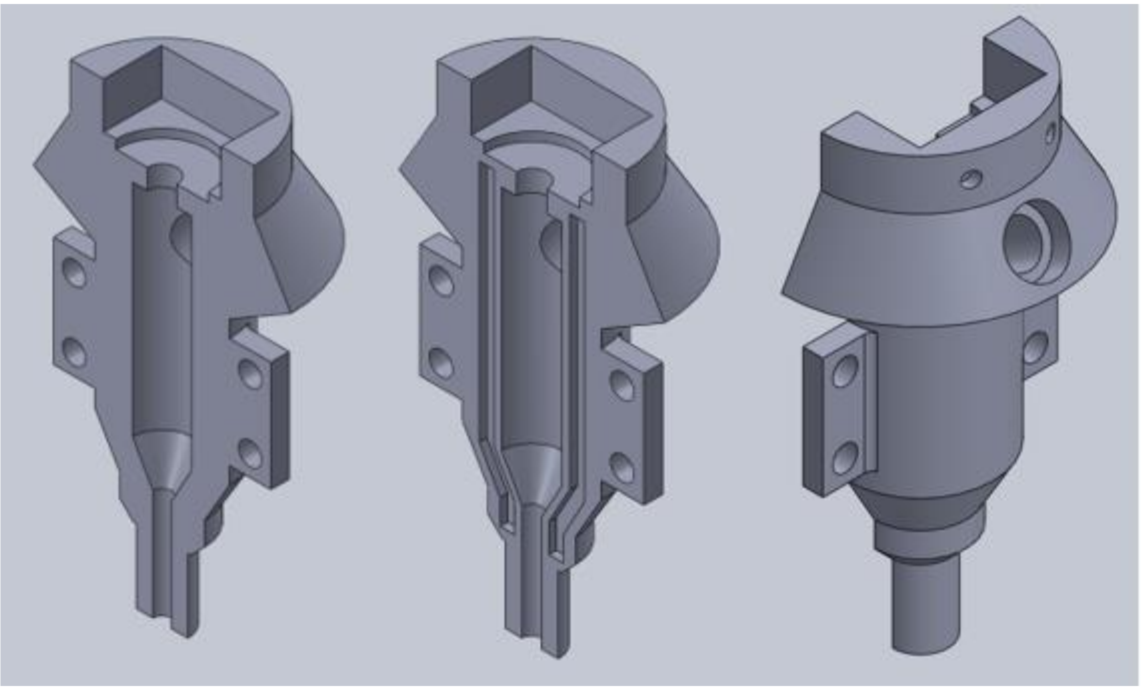

Figure 19: Final Mixing Chamber Design

As mentioned earlier when we were first testing the possibility of printing silicone using our prototype, we discovered that the initial 2mm ID / 4mm OD pneumatic tubing we were using to transfer the silicone was too small. Both the viscosity of the silicone we were initially using, and the small size of the tubing did not allow the silicone to travel out of our syringe input system. Despite the usage of a large stepper motor, the motor was not able to apply the necessary amount of pressure to push the silicone into the tubing. To overcome this issue, we first decided to integrate a larger 6mm ID / 8mm OD pneumatic tubing with larger pneumatic fittings and larger inlet holes to allow more space for the silicone to travel. However, with the Silopren 2670 liquid silicone rubber we were using, the viscosity of the compound was too high to travel more than an inch into the larger pneumatic tubing. At this point we discussed the possibilities of using a different compound and did further research into more applicable brands of liquid silicone rubber. After some research we decided to buy two commercial grade liquid silicone rubber compounds, one for personal DIY (do it yourself) projects, and one for more intricate projects such as ours. After reading the optimal conditions for each compound to cure we decided to only use the compound for more intricate project, the Dragon Skin Fast Cure liquid silicone rubber. With this new compound we were able to push the silicone through the current pneumatic tubing up until halfway through the tubing. The stepper motor we were using for the input system was still too weak to push the silicone all the way into the mixing chamber, but unlike the previous compound we were still able to push the syringes manually by hand to transfer the silicone. We decided to focus on this temporary solution with the less vicious silicone compound to conduct our tests.

During the process of updating the prototype printer for print test, we identified possible additions that would be beneficial for the testing process. We determined that a small dc fan mounted to the moving platform that was pointed at the heat sink between the mixing chamber and heating system would prevent the heat sink from melting the plastic of the chamber. A small 3D printed mount was used to secure the fan to the moving platform directly a few inches away parallel to the heating system. Afterwards we realized that additive heating would aid the curing of the printed silicone, thus we created a custom heated air pump using an aquarium air pump that passes through a custom 3D printed adapter into a similar 3D printer heating system. The heat air pump adapter and heating system were mounted directly to the moving platform a few inches away from the extrusion mechanism on the opposite side of the chamber from the dc fan, pointed at the print bed to heat any silicone extruded onto it. Both the dc fan and the heated air pump are shown in Figure 20 below. Also, to improve the movement of both the moving platform and the XY axis table, we sanded the plywood platform and loosened the railing system, respectively.

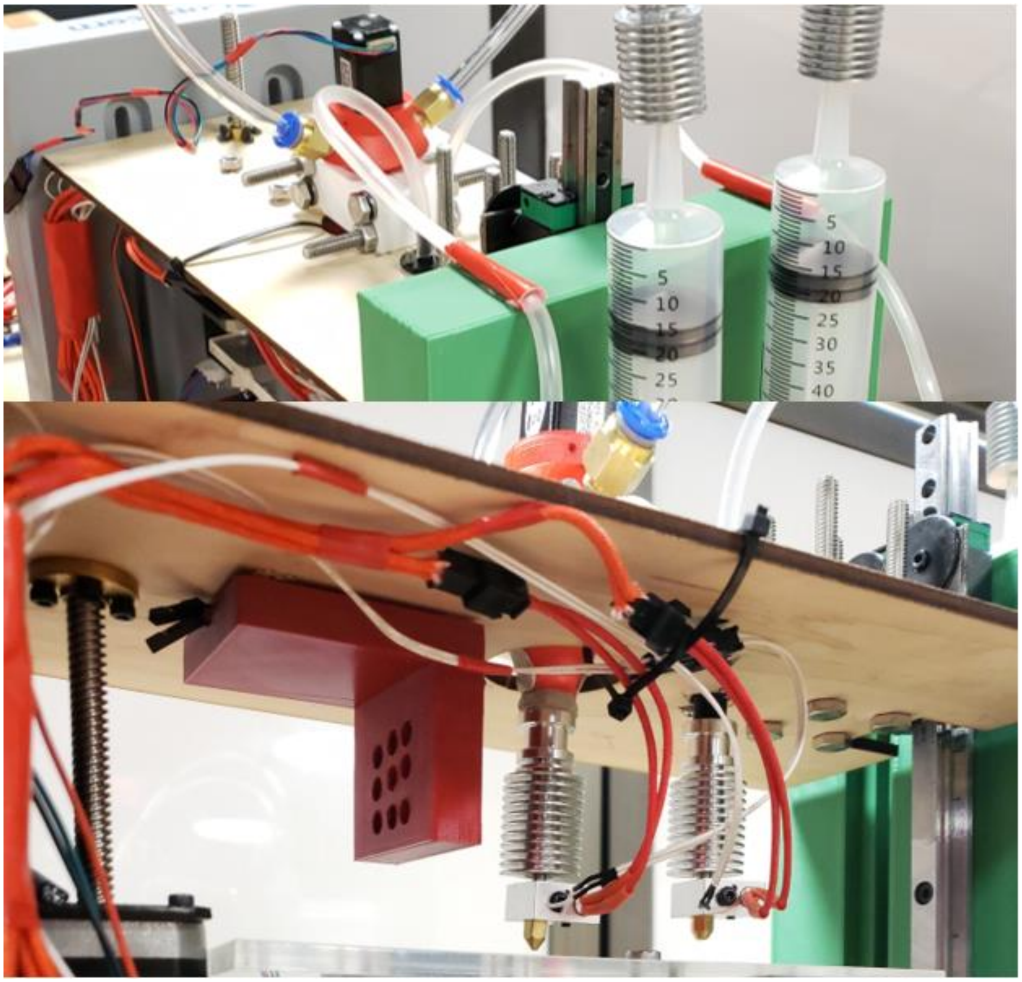

Figure 20: Hot Air Pump and DC Motor Addition

While implementing the previously mentioned modifications and during the initial process of testing, we discovered that we needed to change certain electronic components, add additional features, as well as conduct routine maintenance and rewiring as shown in Figure 21. During a routine mixing and extrusion test, the dc motor being driven by the RioRand was irreparably destroyed and work needed to be done to change over to a stepper motor powered mixing screw. In order to do this, the second extruder section was to be used, which lead to the need for a new A4988 driver to plug into the E1 section of the board as well as the stepper motor connectors above the driver in the correct orientation (blue, red, green, black). Also, with the addition of the new pump and heat block added, a new thermistor was connected at T1 as well as its heating element plugged into D9.

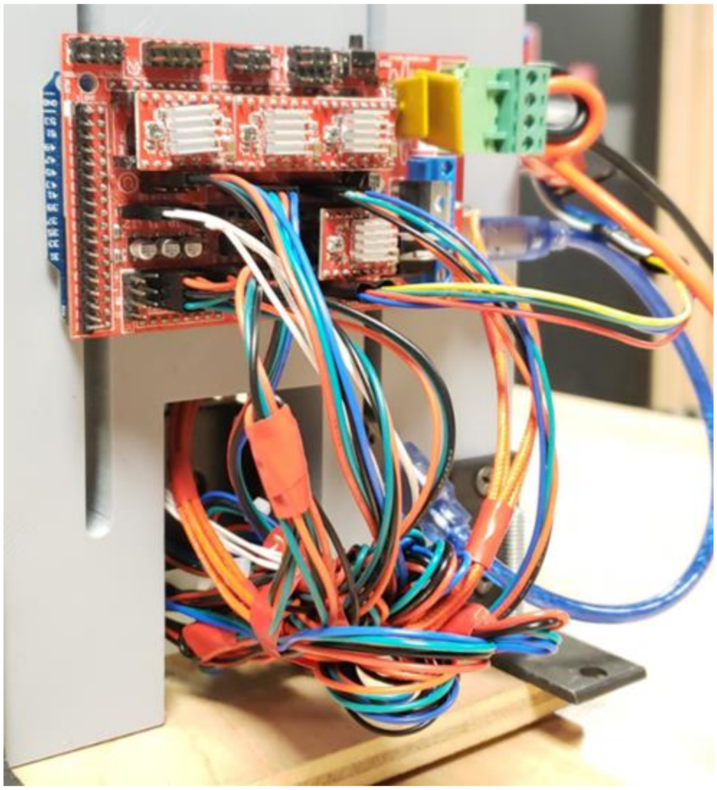

Figure 21: Final Arduino Board and Wiring Layout

Along with the implementation of the new mixing apparatus and heater, we were preparing for the linear testing phase, requiring full automation of all movements as an end goal. The first and most important step of this was making sure that the X—Y table does not impact the side walls or move outside of its allowable range. This would be done by placing end stops on one end for each axis of motion: x and z axis at their minimum in the negative direction, and y axis at its maximum in the positive direction. To set up the end stops, we plugged in the X and

Z axis wires into the pins directly above the X and Z label respectively, while the Y axis wires were then plugged into the pins directly to the right of those above the Y label. This was done following the color-coded diagram below seen in figure 22.

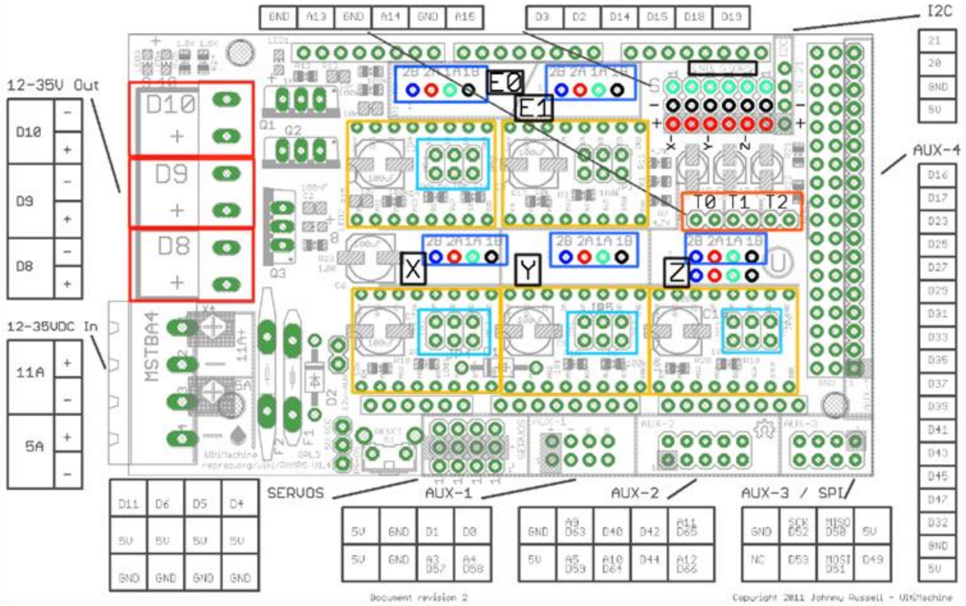

Figure 22: Modified RAMPS 1.4 Diagram (RAMPS, n.d.).

In order to prepare for a full run of the printer, a rework of the extrusion mechanism was attempted by replacing the integrated lead screw stepper motor with a better quality, high torque motor of identical size. The original stepper motor was unplugged from E0 and the new one was plugged attached in its place. Additionally, following testing of the end stops, it was found that a delay was present between unplugging the power supply unit and the printer ceasing operation. This short window of time was ample enough for potential damage to be caused, proactively we began working on a kill switch connected directly from the positive lead on the power supply to the board. This allowed for instantaneous ceasing of operations if ever something went awry, this implementation allowed for frequent testing with a reduced risk of downtime due to mechanical or electrical damage.

With the electrical component additions and vast alterations, many aspects of the configuration file needed to change. This included a change of the Baud Rate of the printer from 115000 to 250000 on line 123, this allowed for reduced response times between commands and movements. Of the physical changes requiring reworks to the configuration, the requirement of a second hot end to the printer as well as the addition of a second extruder in the form of the mixing chamber required the changing of the motherboard designation, because in the EFB setting, D8 was used for the heated bed, D9 supplied power to cooling fans, and D10 powered the only extruder hot end in the system. This is easily remedied, however, by changing the board over to the BOARD_RAMPS_14_EEB configuration in the settings, as seen in figure 23.

```
129 | #ifndef MOTHERBOARD
130 |   #define MOTHERBOARD BOARD_RAMPS_14_EEB
131 | #endif
```

Figure 23: Marlin 2.0 configuration.h, Line 129-131

For the mixing chamber motor control, if two rotational speeds needed to be individually addressed between the two motors connected to the extruder group this needed to be manually unlocked in the configuration file. To do so, we needed to uncomment:

```
738 | #define DISTINCT_E_FACTORS
```

Figure 24: Marlin 2.0 configuration.h, Line 738

This allowed for alterations in the steps per unit and, in turn, the speed at which motions would be done by the mixing chamber while not dictating the same of the pressure regulation system. This allowed for mixing screw speed to become a variable for testing and would be changeable between runs. As for the heat block running as part of E1, the temperature sensor had not been initialized prior to its addition. This meant that for the temperature to be regulated and the system not to induce the printer kill function, T1 would need to be implemented. The thermistor used by the new heat block is identical to that found within the original heat block and so the same tag used by T0 can be used by T1:

```
418 | #define TEMP_SENSOR_0 11
419 | #define TEMP_SENSOR_1 11
```

Figure 25: Marlin 2.0 configuration.h, Line 418-419

In conjunction with the implementation of the heated air nozzle and new mixing chamber motor, the addition of end stops brought us into the territory of fully automated printing by inducing limits on the motion of all axes. However, in order to make the switches already fastened to the printer function properly, steps must be taken to configure them properly, we started with the defining of which end stops were to be used by Marlin, additionally, any plug defined also required inversion, these edits seen in figure 26 below.

```
624 | #define USE_XMIN_PLUG
625 | //#define USE_YMIN_PLUG
626 | #define USE_ZMIN_PLUG
627 | //#define USE_XMAX_PLUG
628 | #define USE_YMAX_PLUG
629 | //#define USE_ZMAX_PLUG
[…] |

658 | #define X_MIN_ENDSTOP_INVERTING true
659 | #define Y_MIN_ENDSTOP_INVERTING false
660 | #define Z_MIN_ENDSTOP_INVERTING true
661 | #define X_MAX_ENDSTOP_INVERTING false
662 | #define Y_MAX_ENDSTOP_INVERTING true
663 | #define Z_MAX_ENDSTOP_INVERTING false
```

Figure 26: Marlin 2.0 configuration.h, Line 624-664

After the pins were initialized, the direction in which the stepper motors would start moving to reach the switch had to be determined. This was done through trial and error, using a separate stepper motor connected to the axis being tested in order to find out if the direction was correct, otherwise edits and a reupload to the Arduino was required. But before any reliance could be put upon the limit switches, as we only used one side, the bed size had to be determined for the software end stops on the anterior side to take effect. This required the measurement of usable bed space and for such values to be implemented into X and Y maximum positions. Figure 27 is the resulting code for the limit switch direction as well as the software-based stops on the opposite side, this can be seen down below.

```
1121 | // Direction of endstops when homing; 1=MAX, -1=MIN
1122 | // :[-1,1]
1123 | #define X_HOME_DIR -1
1124 | #define Y_HOME_DIR 1
1125 | #define Z_HOME_DIR -1
1127 | // @section machine
1129 | // The size of the print bed
1130 | #define X_BED_SIZE 30
1131 | #define Y_BED_SIZE 85
1133 | // Travel limits (mm) after homing, corresponding to endstop positions.
1134 | #define X_MIN_POS 0
1135 | #define Y_MIN_POS 0
1136 | #define Z_MIN_POS 0
1137 | #define X_MAX_POS X_BED_SIZE
1138 | #define Y_MAX_POS Y_BED_SIZE
1139 | #define Z_MAX_POS 200
```

Figure 27: Marlin 2.0 configuration.h, Lines 1121-1139

After all our integrated system modifications, our current prototype has greatly improved both in its functionality and its ease of usage. The project has little to no issues with setup for printing conditions, has an integrated emergency power switch to stop the printer in case of an issue, moves relatively well with minimal to some swaying of the print bed, as well as fully routed wiring and well-organized electrical components. Every component is either secured with hardware or hot glue to maintain the same printing conditions throughout testing. This, along with the myriad of additional variables now tweakable and able to be optimized gave us a versatile testbed to approach testing with. The final layout of the prototype printer can be seen in figure 28 below and all of the CAD models for the entire printer, its components, and the final version of the code, can all be found in our Microsoft Teams folder located here. Alternate views of the final layout can be seen in Appendix B.

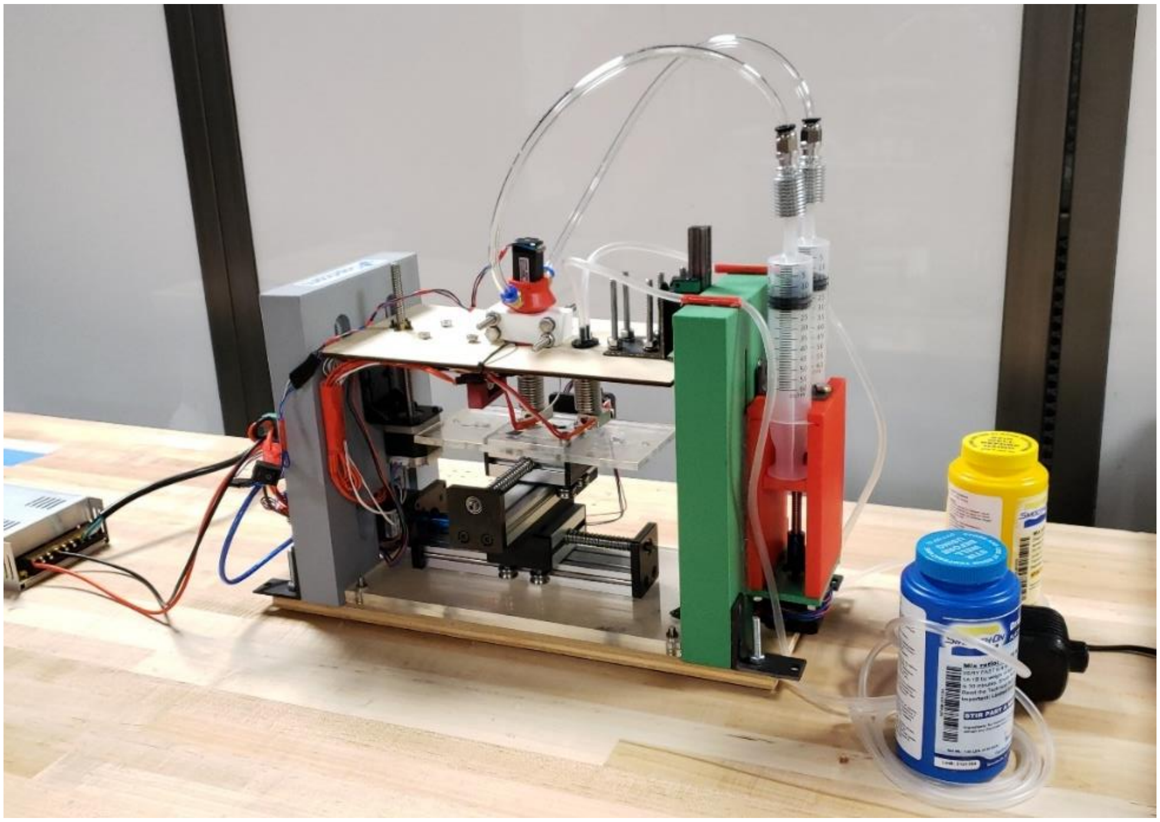

Figure 28: Final Prototype Printer Layout

Silicone Print Testing

Testing Configuration

Actions needed to be taken prior to every test to ensure full functionality, this takes the form of both configuring and consistently checking the current configuration of our main applications and software. Although our Arduino Mega runs Marlin, there was no means of connecting directly to this software to induce motion or any other functionality. Pronterface, an application within the open-source software suite known as Printrun, gave the printer a reasonably simple user interface capable of communicating with the printer via a computer connected to the board through USB. This software gave us the ability to send print jobs over to the printer with ease as well as monitor all the components of the printer that were currently connected to the board. Also, if a critical error ever did occur, all the processes were fully detailed on the right side of the application, allowing for backtracking in order to solve the issue quickly. The application also gave an 3D model that updated as it went, which helped many times in determining the progress of an attempted print.

With the only other way to operate Marlin having been a small LCD screen and directional buttons, Pronterface allowed for far greater control over the initialization of our testbed. While the readouts of temperature and estimated print times on a small screen would have proven comparable to Pronterface and prints could be transferred to the printer via SD card if necessary, these are the only necessary traits of a finished printing platform. Our printer was an experimental and constantly evolving platform that required consistent variations as we pushed towards the printing stage. With Pronterface, any issues faced when changes were made became instantly apparent with an error log that gave the exact failed action and a potential error code. This, along with the ability to manually move the stepper motors at varying speeds allowed for the dictation of maximum speeds, for both mobility and extrusion, later within testing. Pronterface was a pivotal tool in the early stages of the platform as well as during manual testing as it allowed for the setting of multiple temperatures as well as the effective mixing of the liquid silicone rubber.

Mechanical Testing

The first set of print testing that we were able to conduct was through solely mechanical methods without any gcode, the programming language for CNC (Computer Numerical Control) machines such as 3D printers. Our first ever test was to see if the whole system could mix the silicone compound correctly and push the silicone out of the nozzle onto the print bed. In our terms this was a cold-wet test which means we were not using our heating system at the time but still trying to print silicone. We filled each syringe with one different part of the two-part silicone compound and then proceeded to inject the silicone into the mixing chamber with the dc motor (at the time) simply turned on using the RioRand. Once the silicone reached the chamber it was mixed at a relatively moderate speed, and slowly began to extrude out into a small plastic container on the print bed. After determining that the printer could indeed mix and extrude the silicone compound, we removed the small container and let the silicone cure over night to see any results of the print without the use of heat. The next day we observed that without the heat, the silicone settled in the form of a thin layer in the shape of the container that it was in, similar to the silicone molding process however it was too thin due to the heat not curing the material.

Following the success of getting the heating system to work, we decided to duplicate our first test with the heating system on to extrude a single drop of silicone that would cure. We duplicated the same procedure with the heat on at around 120C, and as the silicone began to extrude it began to cure too fast and created a blockage in the nozzle that created an overflow of silicone. The silicone leaked out of certain areas where there was opening such as the connecting section between the chamber and heating system or the access hole for the motor shaft to reach the mixing screw. Due to the leakage of the silicone, some of the silicone material made its way into the holes of the dc motor and cured within, making it nearly impossible to clean or use again. At this point we decided to swap to the nema-8 motor previously mentioned and tried to use one of the old designs for the mixing screw, the model with revolving slots instead of a spiral as seen in Figure 7 earlier in the paper.

With the new mixing motor and mixing screw, we began print testing again for a drop of silicone to cure properly, but with the same procedure the silicone cured in the nozzle again and caused another blockage. We then decided to reduce the heat to 75C and began testing again, but despite the silicone extruding out of the nozzle it was surprisingly not viscous. It was assumed that the silicone wasn't viscous enough due to the heat so we increased the temperature gradually to test whether it would cure better at a higher temperature, but it was discovered that it was due to the mixing method of the revolving screw. Since the design of the revolving screw were vertical slots separated by a thin wall, any material that was injected into the chamber would rather just sit in the slots and be pushed out of the chamber instead of mixing together properly and thus resulted in a viscous consistency similar to the silicone in its premixed form. After this discover we decided to switch back to the spiral mixing screw design and remained at the 75C temperature and resumed testing. The implantation of the old mixing screw resulted in a semi viscous and slightly retentive drop of silicone to be printed, and thus allowed us to move onto the next stage of print testing of using gcode.

STL Print Modeling

Once we were confident that the printer was capable of mixing and extruding the silicone properly, we moved onto developing gcode for sightly complicated STL print models such as a basic line or wall. The first iteration of our print design was a 0.6mm high, 1.2mm wide prism that spanned the entire y axis down the center, however, this did not give us enough time with the mixing screw engaged to properly mix the silicone before the operation was done, with the only exception being the skirt drawn around whatever is being printed, as per Slic3r's preset. To quickly combat this problem, instead of changing the STL design entirely, we went into Slic3r to mirror the print across the Y axis, giving more time for the mixing process to take place as we manually extruded. However, this was a quick fix and development began on a new 2d path that optimized the little space we had, at only 30mm by 85mm. The path created, seen in figure 29 below, started out as a rectangle for the first 3 sides and then reducing the line length slightly each subsequent line until the final line rests in the center, while still giving enough space between the lines to observe the retention and prevent the resulting print from becoming conglomerated amongst itself.

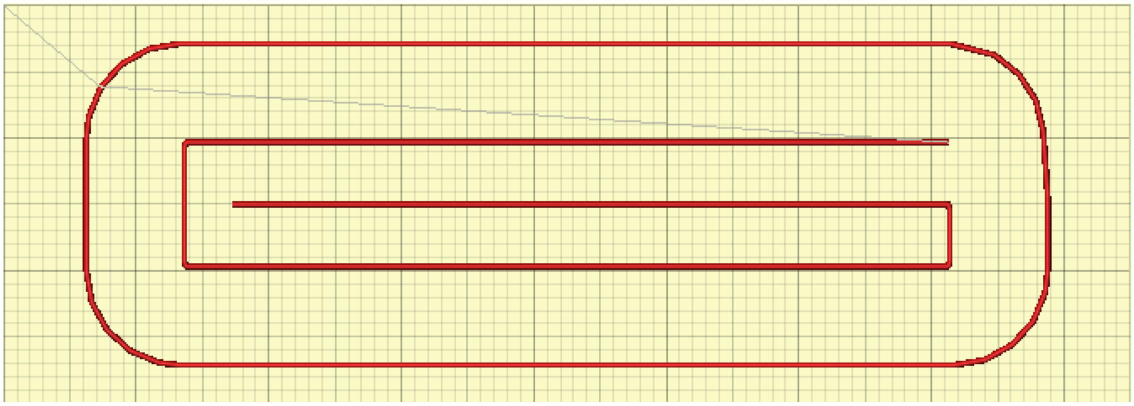

Figure 29: Rotating Line STL Model

In tandem with the STL that maximized covered distance whilst mixing in a 2-dimensional space, we were given a file from Professor Stabile that spanned 3 dimensions. This file was a relatively short object and so a reduction in layer height was necessary at only a 0.3mm raise in elevation after each successful layer. This, in conjunction with faster speeds to compensate for time between non-extruding travelling movements, still resulted in a printing operation that lasted upwards of 7 minutes. The resulting product, if done effectively, would be exactly like the 3-dimensional model seen in figure 30 below.

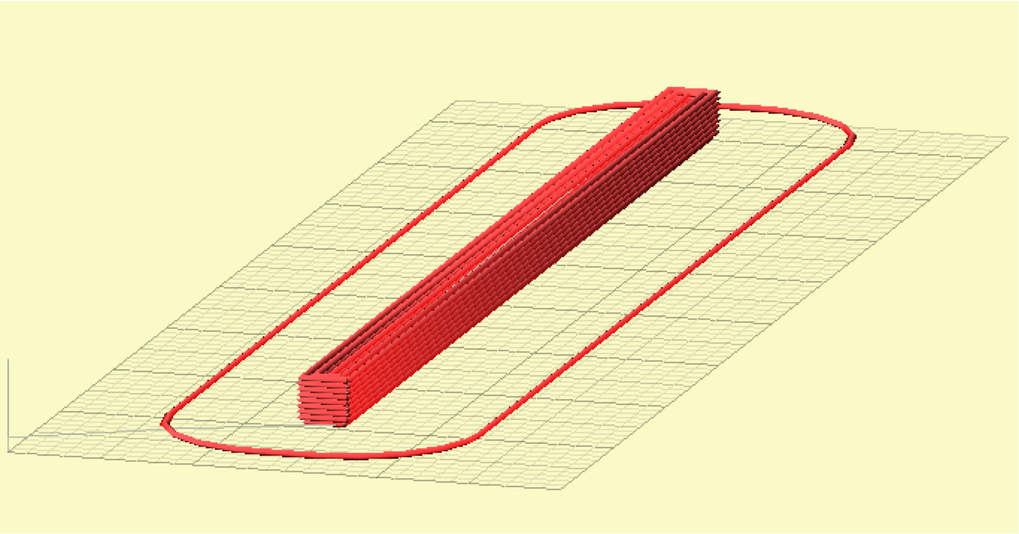

Figure 30: Raised Wall STL Model

The alterations on the side of speed and layer heights were all due to Slic3r, a pivotal application for the conversion of 3D models into the many sequences seen within the printing process using instructions in the form of code. This gcode slicing program, was what we used to convert our STL test files, along with specific instructions and changed variables, into the code subsequently used by Pronterface. On top of this, Slic3r and Pronterface being within the same program suite gives them the advantage of increased compatibility, as Pronterface could access default settings already set while Slic3r could do the same. The settings and features of both Pronterface and Slic3r continuously proved useful for the alterations of variables that inevitably lead to higher print qualities and more consistent results as more tests were done.

Programmable Testing

After creating the first iteration of the gcode for our STL print models, we began to program the robot to print a line of silicone in hopes to succeed and then print a slightly raised wall of silicone. For us to build a wall we needed a long and retentive line of silicone that was mostly cured but was able to allow silicone to be extruded onto it. We continued using the same format of testing as our previous successful test with the spiral mixing screw, 75C print temperature, and moderate mixing speed. The newest issue we faced was that the temperature was too low when printing a whole line so the silicone that was extruded onto the print bed became a slightly long pool of silicone with a moderately liquid consistency. It was determined that we needed to increase the printing temperature to create a more solidified line of silicone. The printing temperature was then increase to 95C and yielded a more solidified but long puddle of silicone. Despite the success of solidifying the silicone more, it was not retentive enough to be built upon for a wall of silicone, so we had to analyze the optimal solution for a better print.

We replicated the last test once more time to see if it would be able to print a wall of silicone. The silicone was not retentive enough to be built upon and instead continued to pool as we were trying to print proceeding layers of the wall as seen in Figure 31 below. This test helped us analyze the conditions needed to produce the certain print that was created, and we discovered that by increasing the mixing speed of the mixing screw it would extrude a more retentive line of silicone. With the faster speed, the silicone compound is more thoroughly mixed to the right ratio that gives it a more retentive form as it leaves the print nozzle. However due to the faster mixing the silicone spends more time in the chamber when the mixing speed was slower, so it takes longer to leave the nozzle which was hard to time during print tests due to the manual input of the silicone material. With the slow extrusion of silicone, we proportionally decreased the speed of the relative print gcode for each STL model to allow more time for the silicone to reach the print bed before the test was over.

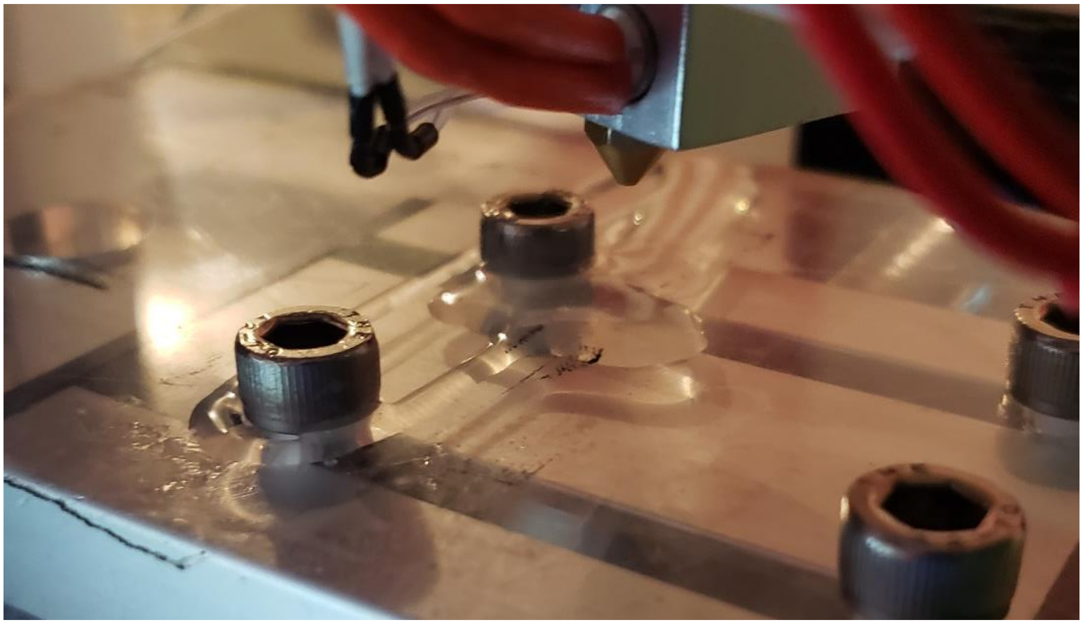

Figure 31: Long Pool of Silicone Print Test

Using a faster mixing speed and lower printing speed allowed us to print a long, slightly retentive (not solidified) line of silicone with a liquid consistency, but we still ran into the issue of the silicone curing within the nozzle and creating a blockage. Since we were unable to print more than an inch of silicone due to the constant blockages, we switched back to printing a single line for the reminder of testing, since it would be necessary to print more than a single line to construct a wall of silicone. As we did previously, we lowered the print temperature in hopes to avoid the blockages, but also tried to increase the pressure applied to injecting the silicone through the system so it would have a faster flow and have less time to cure in the heating system. This unfortunately backfired and lead to a greater leakage of silicone than previous failed tests, due to the missing screw not being able to withstand the pressure of the silicone rushing into the chamber. Once we returned to the normal applied pressure for input, we continued to experiment with temperatures to get the best printed line of silicone in terms of length and retentiveness. We finally were able to print a short, retentive (slightly solidified) line of silicone with a gel consistency with a length of 2 inches shown in Figure 32. This was determined to be a satisfactory conclusion for the testing for our team, and we began recording and analyzing the procedures and results that were present throughout testing.

Figure 32: Short Retentive Line of Silicone Print Test

User System Procedures

Before every print test, we ran through a set of preliminary procedures to ensure the printer was in the optimal condition for testing to occur. First of which was to ensure everything disconnected for storage or for cleaning processes was fully reconnected, these included the mixing screw quick-disconnect section and the 2 pairs of heating elements and thermistors. Second, was to connect to the printer through Pronterface, we selected the proper COM port used by the Arduino Mega, ensured a baud rate of 250000, and pressed connect. Once the printer and computer were connected, the controls on the left-hand side of the screen would light up, from there it was paramount that the maximum speeds at the top were checked to keep them within the reasonable values of 350 millimeters per minute for the X and Y axes and 200 millimeters per minute for the Z axis. In terms of other settings to be checked, we needed to ensure that the number of extruders was still at 2 and that both were fully functional by watching the temperature graph, observing temperature trends for believability.

Once precursory tests were finished, the main power switch would then be set to the on position, which allowed for full functionality of the motors and heaters. With the heater operational and no requirement to manipulated anything near the heat blocks, we then began the process of preheating, safely allowing the hot ends to reach their designated temperatures while the rest of the setup is done. While the heating was under way, we then tested the seating of the mixing screw to prevent impeded movement and jogged each stepper motor axis 1 millimeter to ensure the motors were engaged. If the motor engagement test was nominal, the next step was to home all of the axes as a test for all of the limit switches, for the duration of the test, we remained ready to flip the kill switch if any components pushed past a switch, this prevented unnecessary damage, if anything had gone awry.

Regardless of the test at hand, the printer was now deemed ready for testing, the only step from here was to select and load a prespecified gcode of our test STLs with the settings pertinent to the test at hand. This gcode would then be ran in dry mode to ensure all was working correctly, this run would start quickly as the printer had been at or near temperature since the beginning of the printer’s full utilization of power. This dry run is then closely observed and timed to ensure that enough time would be allowed for a properly mixed extrusion attempt. From here, the syringes were then connected and depressed far enough that both parts of the compound were close to the mixing chamber. The wet test would then commence, as the printer went through the designated motions, we were ready to manually extrude the silicone at a point previously specified on its path and ultimately placing the LSR onto the acrylic print bed.

After every print and before the next print test, we also had to thoroughly clean the whole extrusion mechanism and heating system of all remaining silicone. The difficulty of cleaning the system was determined by the solidification of the silicone within. Usually at the end of the heating system the silicone would be fully solidified due to the heat and if left to sit overnight all the silicon in the chamber would also be solidified. However, in certain failed tests or periods of time where we conducted multiple test back-to-back, the silicone would be liquidly with a viscous consistency.

No matter the test results, we used the syringes to suck out any silicone within the pneumatic tubing and the inlet holes back into the syringes. This allowed us to reuse the syringes for testing, however after a few tests the silicone that was being sucked into the syringes began to form multiple air bubbles and to avoid this we deposited the silicon into their containers and used new syringes when necessary. After the silicone was stored in either the syringes or their containers, we removed the tubing and syringes from the mixing chamber and left the connecting pieces to the side to be cleaned while we usually threw away the length of tubing used for testing. Unlike the syringes the tubing was not an optimal place for silicone to settle and it was nearly impossible to remove all the remaining silicone out of the tubing during testing so when we weren’t reusing syringes, we threw away any length of tubing we used that had silicone stuck inside. Next, we unmounted the extrusion mechanism form the moving platform and disconnected the supports and heating system from it. All hardware and parts were separated and then layout to be cleaned by hand.

To clean the parts after the silicone had time to solidify was as simple as ripping off the silicone that was stuck to the parts and throw it away as shown in Appendix B. When the silicone wasn’t solidified each part had to be wipe down to remove the initial layer of silicone, and then a thin metal pipe cleaner brush was used to remove any silicone stuck inside or on components. After every part is brushed off, it is then once more wiped down before it is all reassembled and remounted to the moving platform. Once the extrusion mechanism and the heating system is in place, we would either get the syringes and tubing ready for the next test or leave the printer in its most recent state until our next test.

Results and Analysis

Current Printing Options

Through the compilation of all our testing we were able to determine that our printer is capable of printing primarily three options of silicone print qualities. We started the project in hopes to print a long, retentive (moderately solidified) wall of silicone with a gel consistency but were only able to print a short line of silicone. The first quality of silicone printing is a long pool of silicone with a moderately liquid consistency with the usage of a moderate mixing speed. Depending on the type of silicone compound that is used, especially a more viscous compound as an example, would be capable of yielding successful prints. By either increasing the printing temperature or mixing speed you would have a short, slightly solidified line of silicone with a paste consistency or a long, slightly retentive (not solidified) line of silicone with a liquid consistency, respectively. Both results are improvements from the first result but not optimal for further complex 3D print models. Finally, our most successful result was a short, retentive (slightly solidified) line of silicone with a gel consistency which if it were capable of printing for a longer period without any blockages would be the optimal condition for printing a wall of silicone or any prints that require multiple layers. The retention is important so that the print would not pool or slowly flatten as more silicone is added on top of itself, and the solidification will allow the print to cure faster and lead to more preferable print times. Once necessary modifications and further tests are completed along with the design of experiments that is currently recorded, the prototype printer could be used for personal use.

Future Printing Possibilities

Striving towards the ideal combination of a retentive printed material with extrusion only limited to material held and not by time held within the nozzle, is a difficult optimization problem to be solved and one that may have a fix simply from more testing. Some ways that more could be tested with the current iteration of the printer would be increasing the movement speed of the X and Y direction while reducing the distance between the tip of the nozzle and the bed between prints. This may be able to continuously remove material from the nozzle by way of friction, however there is already a limit to this reduction as the material has the possibility of forming around the tip and curing just as quickly. Additionally, when the movement speed is dramatically increased, the time between travel operations may be short enough to not need to worry about the curing within the nozzle between extrusions. Something that needs to be worked upon throughout would be the temperature at the silicone extrusion nozzle and at the air pump heat block. The reduction of heat at the silicone nozzle and the increase in heat at the airflow region would be a prudent first step as the silicone could possibly cure from the high ambient temperature outside of the nozzle rather than the high heat inside the nozzle.

Conclusions and Recommendations

Prospective Improvements

The quality of a testing platform has a direct impact on the consistency and on the probability of positive testing outcomes. The implementation of a new pressure regulation system, or at the very least a full optimization of the current stepper motor driven assembly. Over many iterations, the direct linear actuation method continuously failed due to a lack of torque from a single stepper motor, for the stepper motor driven solution to have any viability, there must be a heavy utilization of mechanical advantage, a large enough stepper motor that can withstand the pressure, or the addition of more motors. However, there are still drawbacks to all of these, there was always a high amount of latency within the system as movement started seconds after pressure was applied and took equally as long to stop when pressure was released. While a stepper motor-based system is the cheapest and easiest to implement within the RAMPS 1.4 platform, the latency inherent with the method leads to a lack of precision, which is a large tradeoff to be had. A more difficult option but more rewarding option in the long term would be the implementation of an electronic air pressure regulation system using an auto glue dispenser, such as a 110V Auto Glue Dispenser, coupled with and air compressor capable of 1.5HP or more. One notable feature of this system is that unlike the stepper motor system, this uses negative pressure in order to retain material post-extrusion. Regardless of the means by which it happens, the extrusion mechanism needs to be redesigned in order to automate extrusion within the gcode.

Of equal importance the extrusion method, the addition of a more effective external heating method must be done in order to more consistently print more than 2 inches of thoroughly mixed silicone. If the silicone was able to be heated by a source outside of the nozzle, the material still achieves the optimal temperature for rapid curing while reducing the necessity for a heated nozzle, which has continuously been a source of premature solidification. Our current convective heating solution is not aimed at the material coming directly out the nozzle; therefore, the heating effects are less impactful at the one place requiring high levels of heat. Additionally, as seen multiple times, on contact with the heating element at around 80℃ leaves the silicone fully solidified in rapid fashion. This solidification on contact phenomena could be used by implementing a heated bed at a high temperature along with some form of convective heating directed at the point of contact between the silicone mixture and its target location below the nozzle. All the while, there can be less importance on heating the material directly out of the mixing chamber where it will settle whenever motion without extrusion occurs between layers.

Once print quality reaches a higher standard to the point where steady printing is a more feasible concept, having a higher quality testing platform that allows for more control over fine movements and a larger print surface than the current 30mm by 85mm. The current system in place has much instability within the x and y axes as the sliders consist only of simple railway wheels on the sides of the track and no other method of retention, leaving the print bed wobbling during motion. It would be best to recreate the means of articulation within all axes, the x-direction being under the print bed fully restricted all motion in that direction as the bed was constantly at risk of hitting either of the walls of the printer. To improve this, the mixing chamber would be mobile upon the x-axis instead on a slider driven either by a lead screw or pulley. The y-direction would remain under the print bed with it now being much lower to the base of the printer. For the z-direction, a second identical stepper motor and lead screw would replace the problematic slider on one side of the printer, resulting in a stepper motor on both sides and in turn less instability or failure to move. These improvements to mobility would allow the printer to more consistently contact the print surface or even subsequent layers.

Future Impact

With the implementation of necessary improvements, this project could produce a 3D silicone printer on par with the more recognized Wacker Chemie AG 3D printers for silicone or EnvisionTech 3D Bioplotter. Once the printer is finalized, the silicone will yield 3D printed objects with power, durability, transparency, electricity manipulation, and biocompatibility that anyone might ask for. Despite that the majority of usage for 3D printed silicone is still in the medical area, the same advantages that make it great for those applications can easily translate to other fields. Also, when this technology becomes more standard knowledge in the field of additive manufacturing it will opens paths to a multitude of possibilities from intricate prothesis to small silicone speaker components. With enough time academic programs and large 3D printing companies, can start exploring and advancing into a new variety of techniques and material variations further growing the demand for innovation of several printers and services.

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Appendix A: 3D CAD Models

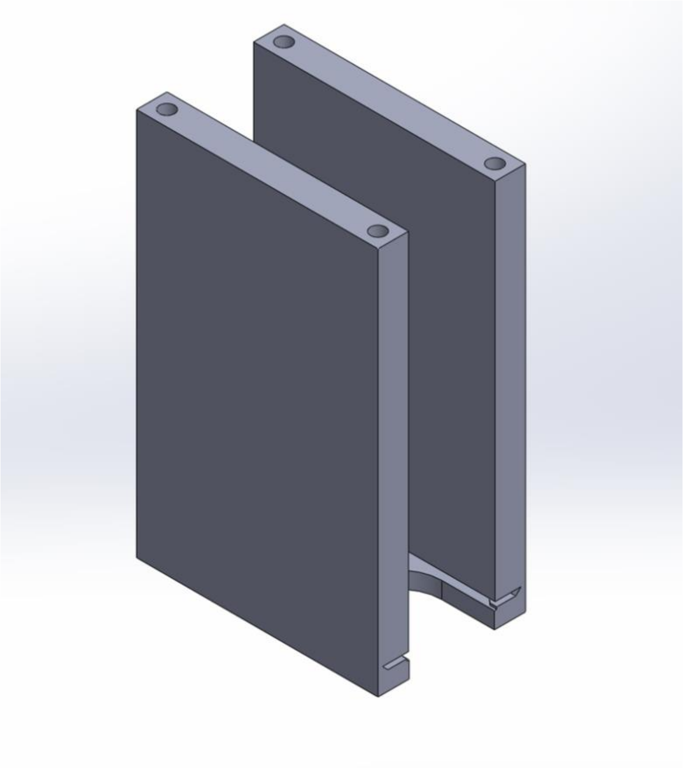

Figure 33: Input System Housing

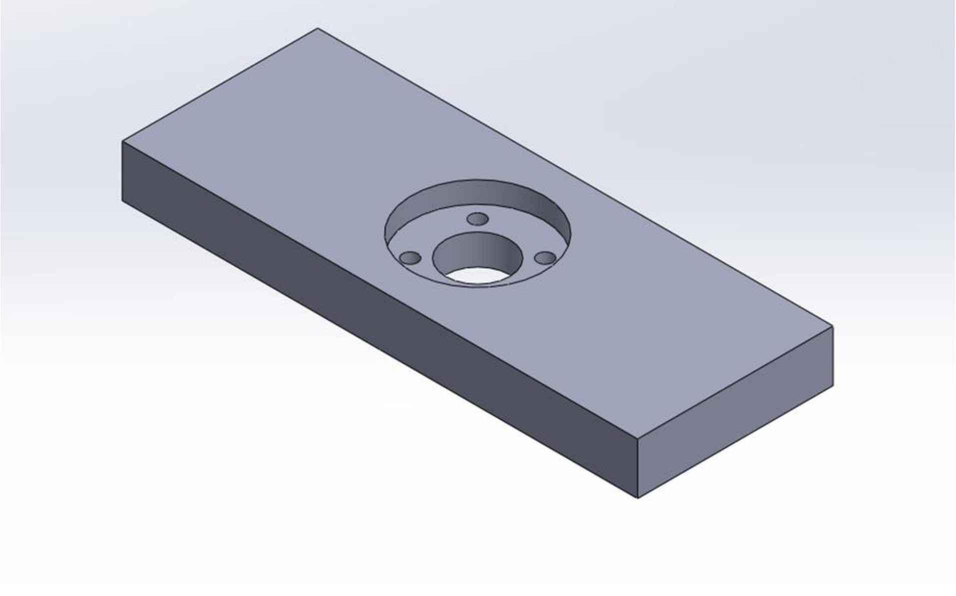

Figure 34: Input System Horizontal Plate

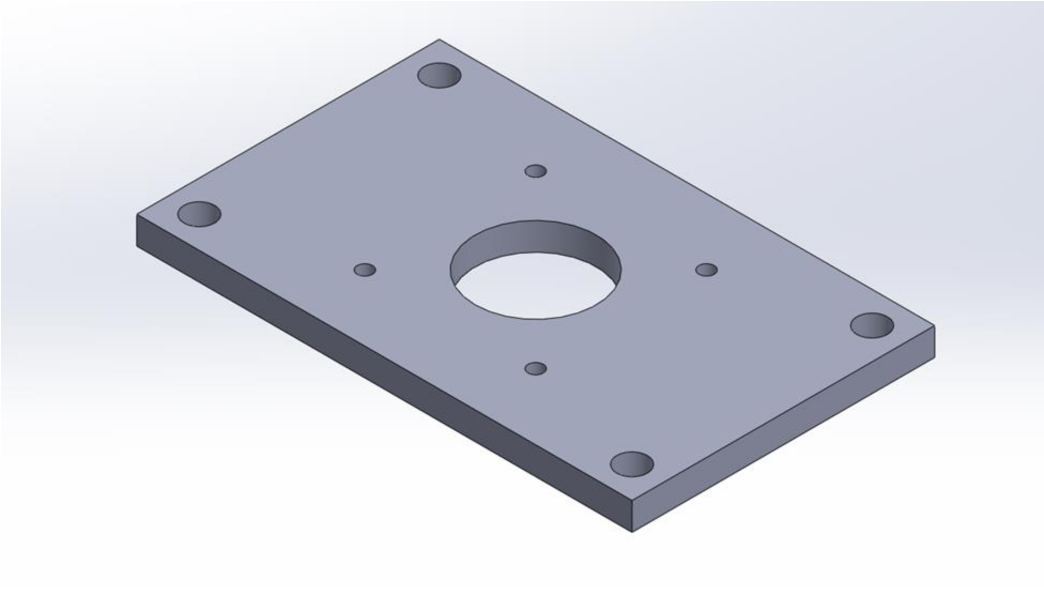

Figure 35: Input System Stepper Motor Mounting Plate

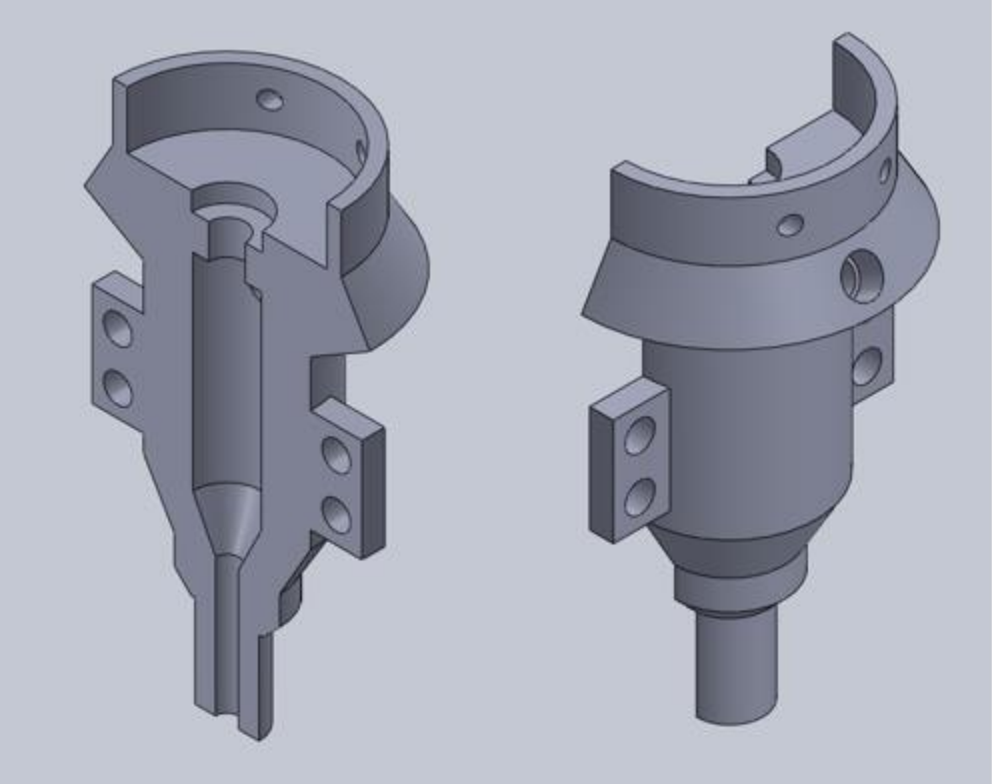

Figure 36: Mixing Chamber with Motor Support Design

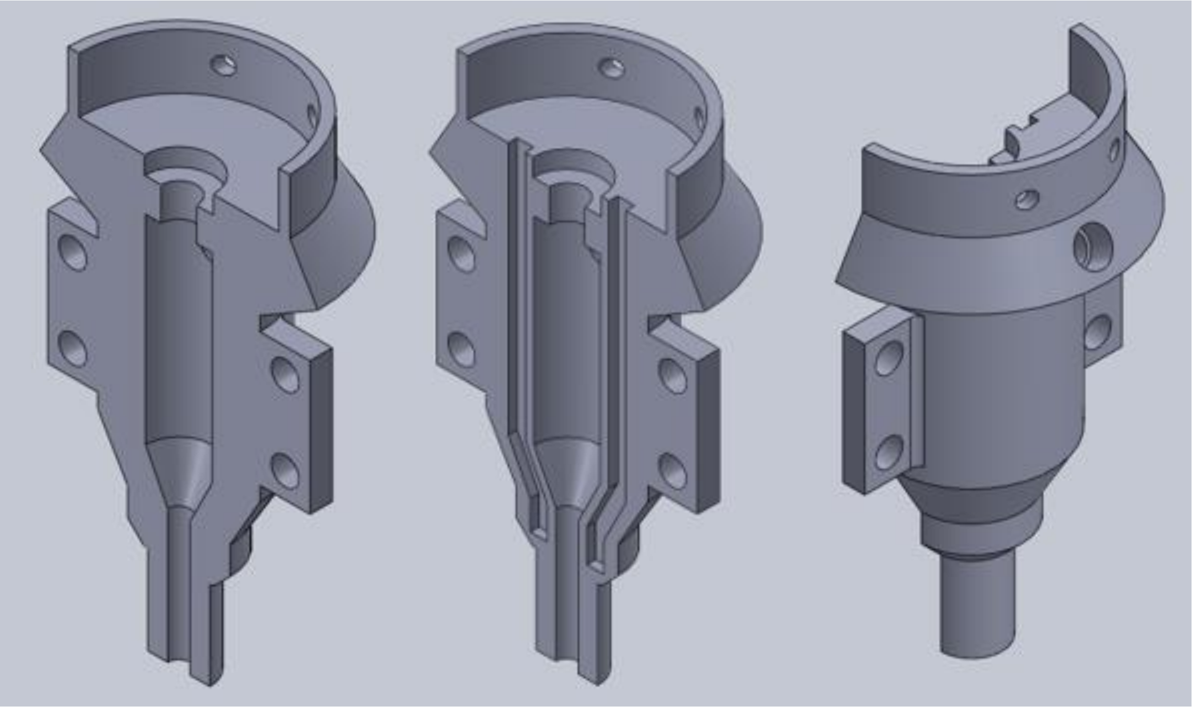

Figure 37: Mixing Chamber with Sealing Channel and Longer Mounting Panels

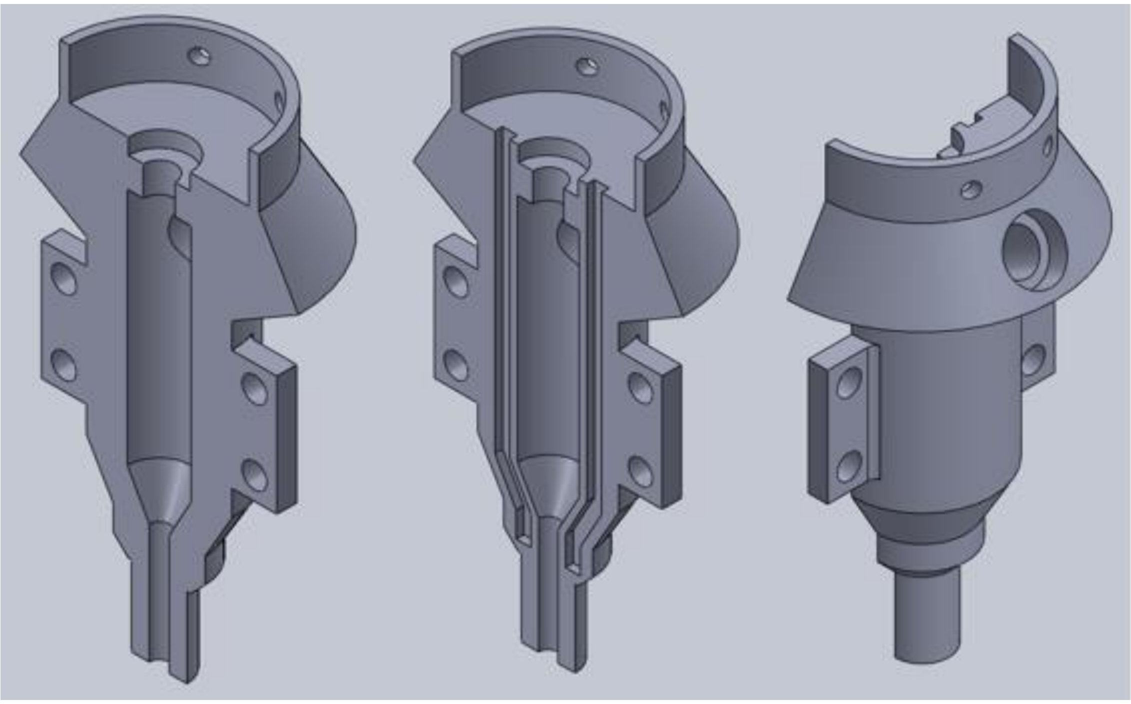

Figure 38: Mixing Chamber with Larger Inlet Holes

Appendix B: Silicone Printer Pictures

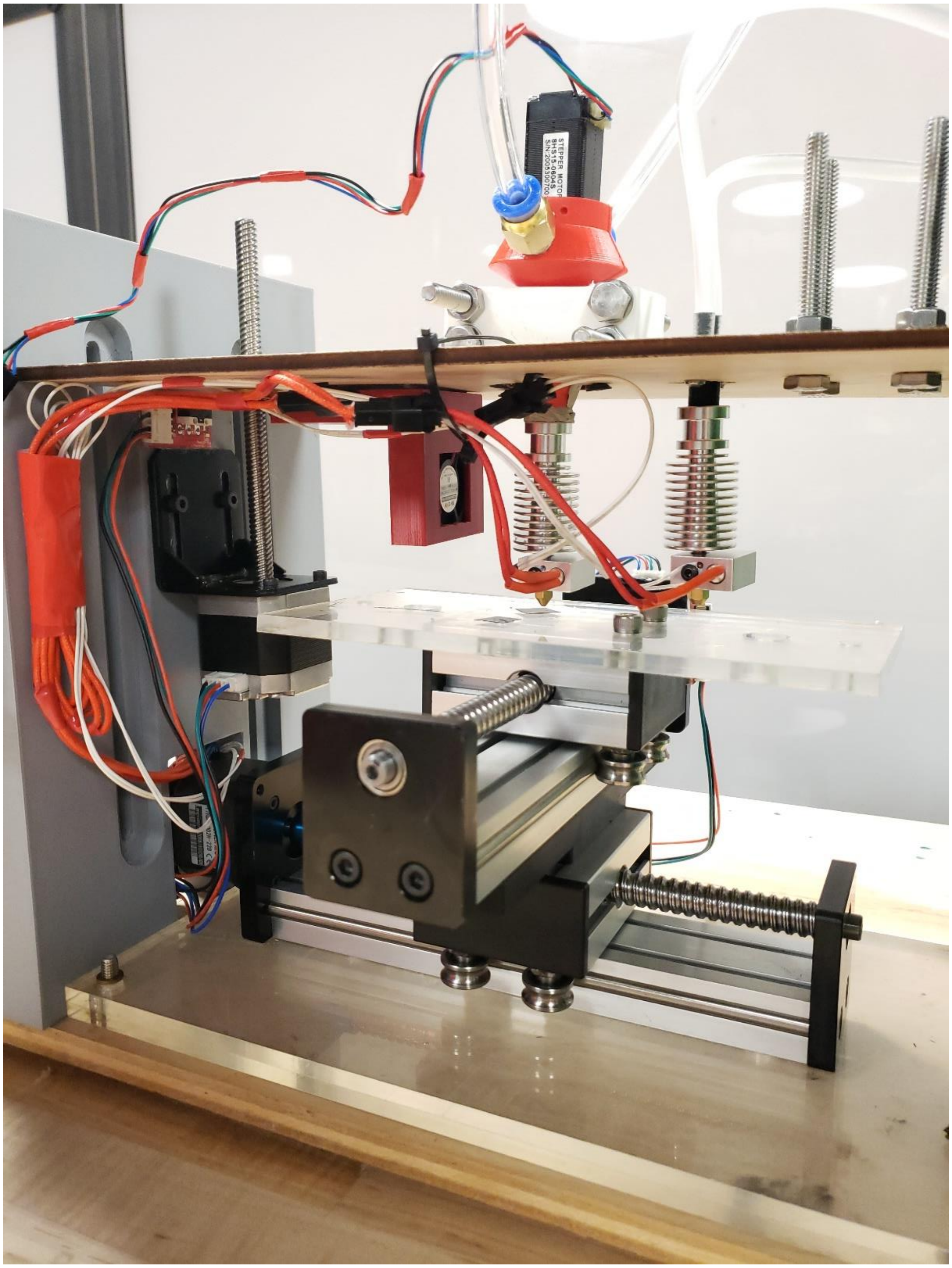

Figure 39: Final Prototype Printer Layout - Front View

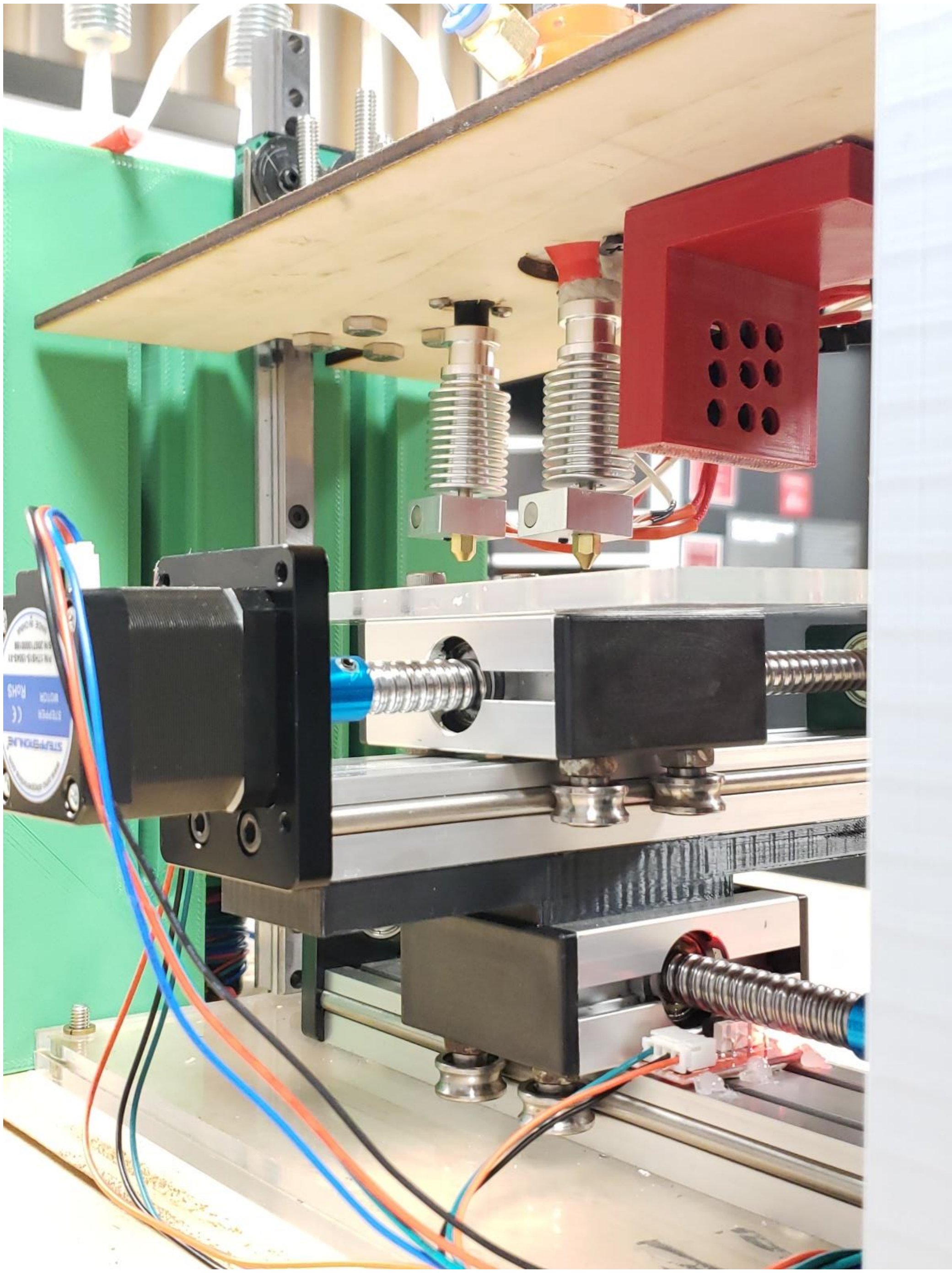

Figure 40: Final Prototype Printer Layout – Low Isometric View

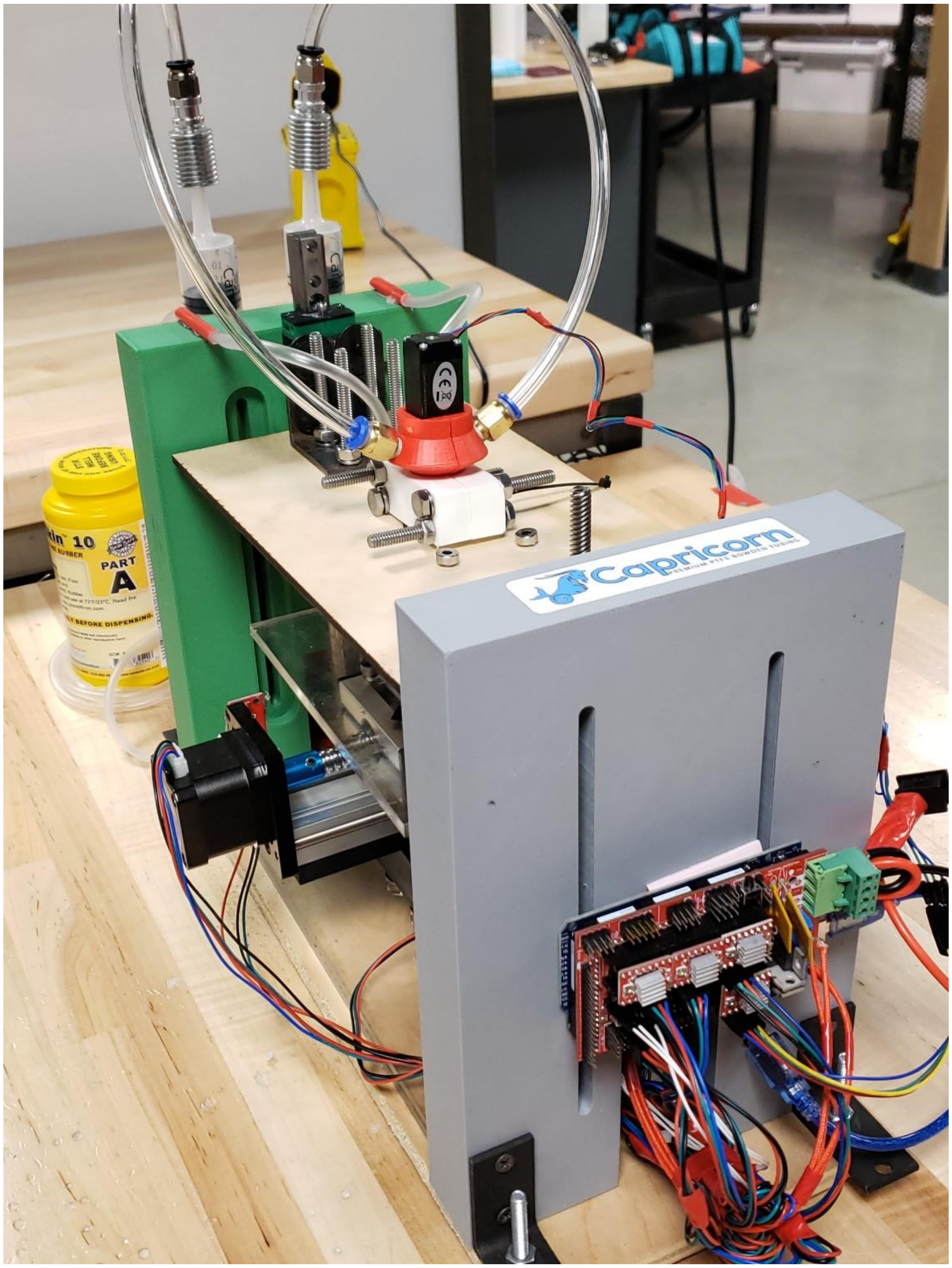

Figure 41: Final Prototype Printer Layout – High Isometric View

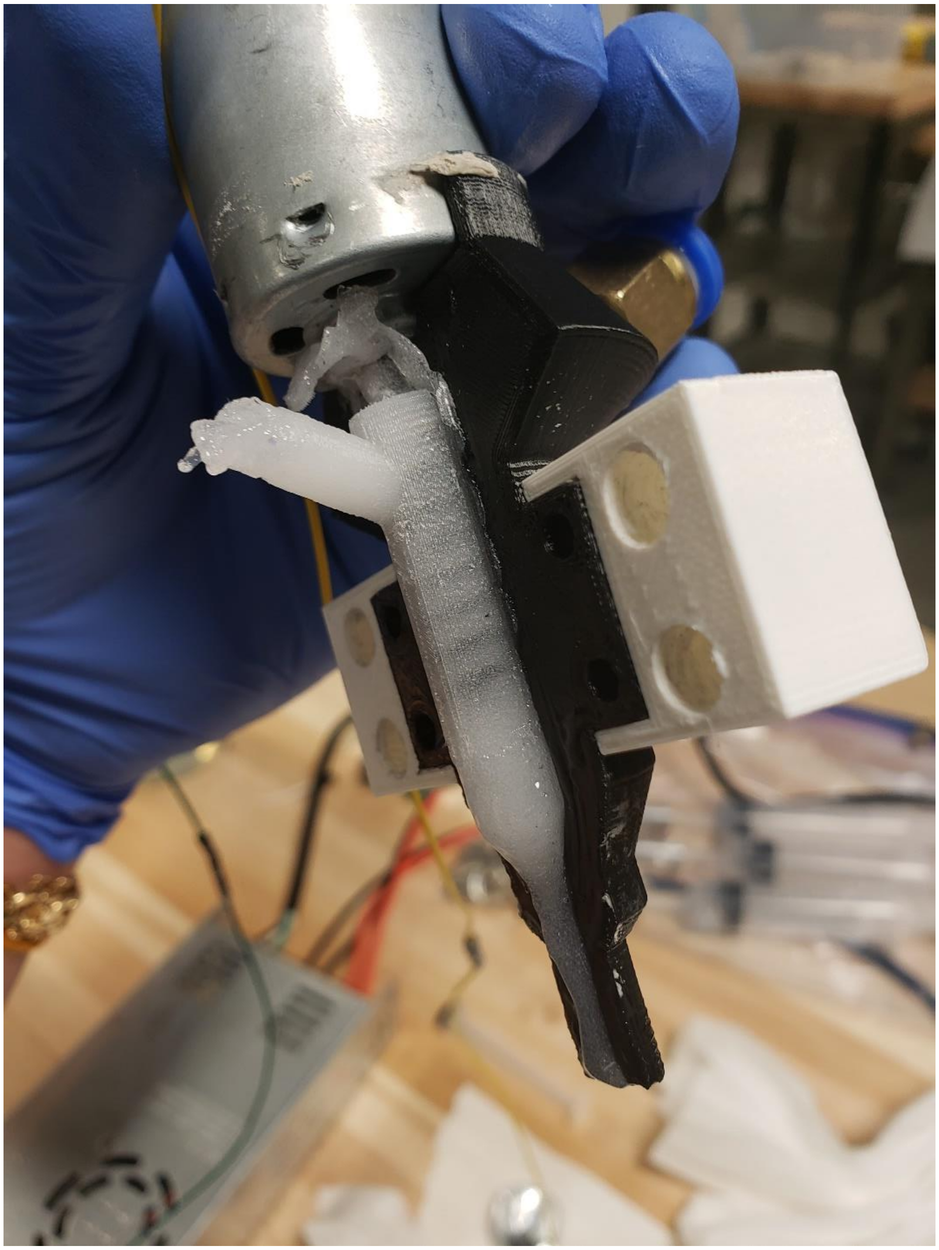

Figure 42: Solidified Silicone in Mixing Chamber