3D Silicone Printing

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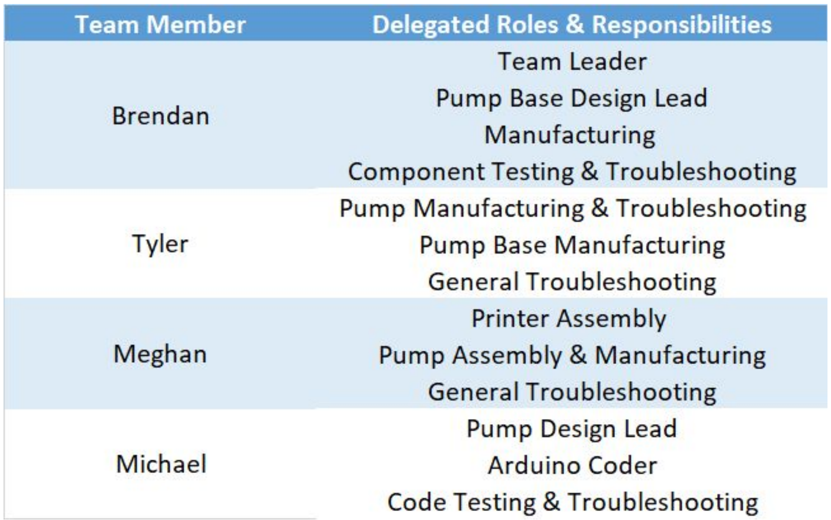
Abstract:

The goal of this design project was to complete the assembly of a 3D printer with the proper modifications to allow it the capacity to print silicone structures. The subsystems of the silicone 3D printer include the main printer, the heater wings, and a syringe pump. In an effort to reduce the total cost of the printer and its subsystems, an open-sourced syringe pump was designed and manufactured. The pump design consisted of a stepper motor coupled to a ball screw to push the syringes at a desired rate. To control its speed, an Arduino Uno was programmed and connected to an easy driver motor controller. Evaluation and testing of each of the subsystems was completed following the design and fabrication in order to assess the performance of each subsystem. The pump evaluation and testing confirmed that the pump could apply the necessary force of approximately 600 N to the syringes while maintaining a steady flow rate of silicone into the print head. The printer assembly was able to be completed, with all of its requirements met, and testing of the motors and programming was also successful. Less successful, however, was the assembly of the heater wings circuitry, which is a crucial component of the silicone 3D printer kit. Due to issues properly wiring the electrical components that control the fans and cartridge heaters, the heater wings were not functional which proved problematic for overall print quality and effectiveness. Several recommendations were made for this design going forward to improve the quality of prints, ease of use, and simplicity of the overall system.

Team Member Roles

Table 1: Team member roles



Team Member	Delegated Roles & Responsibilities
Brendan	Team Leader Pump Base Design Lead Manufacturing Component Testing & Troubleshooting
Tyler	Pump Manufacturing & Troubleshooting Pump Base Manufacturing General Troubleshooting
Meghan	Printer Assembly Pump Assembly & Manufacturing General Troubleshooting
Michael	Pump Design Lead Arduino Coder Code Testing & Troubleshooting

Introduction

The scope of this project and following goals were compiled by the team to be achieved over the course of the academic year. We first aimed to complete the assembly of the Silicone 3D Printer and troubleshoot potential problems as necessary. Our next goal was to design and build a new, cheaper pump alternative due to the fact that the medical grade pumps required for this project were outside of our budget. Thirdly, we wanted to complete a general test print and troubleshoot in regards to the silicone properties to optimize the 3D printed material’s performance. Finally, we wanted to test print a model silicone cervix to compare to the molded samples already available. Of these goals, the group only fell short of being able to properly test and optimize the silicone.

On top of the general goals determined by the team, it was also necessary to create functional requirements so that there were specific performance metrics that could be measured and assessed for the design. In terms of printing speed, ideal performance would require a performance measurement within 20% of the specified printing speed, or a measurement in the range of 5.654-6.911 mm^3/sec. In regards to the silicone mechanical properties, the goal was to have the printed silicone perform within 20% of the Young's modulus of identical molded parts. For the printing dimensions, it was necessary to ensure that the printer utilized approximately 100% of the original 3D printer design print volume (220 x 220 x 240 mm). For the most design-intensive aspect of the project, the pump replacement, precise and consistent release of the silicone mixture to form accurate mechanical properties consistent with a medical grade pump was desired. Finally, decreasing the solidification time of the silicone was desired with the applied heat from the heater wings to the silicone mixture after extrusion.

Properties of Silicone

Silicone 3D printing is an innovative method for designing soft, flexible materials quickly and efficiently. The ability to utilize additive manufacturing techniques can change the way silicone is used and make it more widely applicable. This is especially true for biological applications, where soft tissue manufacturing is becoming an important topic. Additive manufacturing allows for the creation of complex geometries or hollow structures which cannot be easily done with existing methods of producing silicone. One of the greatest challenges with using silicone for 3D printing is that it must solidify quickly, such that the material solidifies shortly after extrusion to create the intended shape. To fix this problem, heat can be added to the silicone to decrease the time it takes for the silicone to solidify.

Silicone is an amorphous material that is typically molded into its shape. This can be attributed to crosslinks in its molecular structure that bind together as the mold changes from a liquid to a gelatinous solid. As is known from the discipline of materials science, crosslinks are known to make a strong, thermally stable molecular structure. They are helpful in solidifying amorphous materials such as silicone to create strength without compromising flexibility.[6] However, silicone is not a relatively strong material; its tensile strength is approximately 10 MPa.[2] Silicone is also known to have a low thermal conductivity and good thermal stability, which makes it a suitable insulator in some applications. Silicone has less variance in its material strength than other materials once subjected to high temperatures of over 100° C.[6] This makes silicone a desirable thermal insulator, which is good for biological applications.

Injection molding,[4] which combines a two-part silicone mixture and inserts it into a mold, has been used to create 3D structures made of silicone. The mixture is a combination of silicone with a cross linking agent and a catalyst that allows the crosslinks to form.[1] The silicone is then left to solidify, which can take up to 24 hours for large pieces of silicone at room temperature before it can be successfully removed from the mold.[7] This is not suitable for 3D printing applications, even when considering that the volume of silicone printing at any given time is much less than the volume of silicone setting in a mold. To use silicone in additive manufacturing, the setting time of the material must be reduced.

Some researchers have found that introducing heat to silicone during solidification has been able to reduce the total setting time. By pouring silicone into a heated mold, the amount of time needed for the silicone to set is greatly reduced.[7] This occurs due to the presence of cross links in the silicone, which proliferate once heat is added. Introducing heat in the setting phase has been widely accepted as a method of cutting down wasted time when molding and preparing silicone. When the temperature of the silicone rises during the curing phase, the crosslink density increases.[5] This implies that crosslinks can form more quickly to achieve solidification when the temperature is elevated. Additionally, the increase in cross link density correlates to a higher overall strength of the material. In some cases, a tempering or post-curing process is added in order to further increase the crosslink density and increase the strength of the material to meet given requirements.[1,3]

It is clear that there is much information and knowledge available about silicone from a molding standpoint. With this in mind, it is important to explore how the properties of silicone can relate to its use in an additive manufacturing environment, despite some difficulties faced to this point. Certain properties of silicone make its 3D printing possible and increases the variety of applications as discussed below.

Silicone Hardware Integration

A traditional 3D printer is typically designed for use with a variety of standardized plastic and resin filaments.[8] It can, in its intended and original configuration, ‘print’ small objects additively—however, its supported materials list comprises entirely of rigid materials such as PLA/PP plastic-based filament, as most 3D printers historically have been. As the timeline of 3D printing’s development has become accelerated, different production methods and materials used have begun to emerge.

One example of this atypical material use is the creation of 3D printed shape memory polymers (or SMPs) which yielded results when it comes to printing and using flexible structures.[9] Additionally, various metals are now seeing utilization in additive manufacturing due to recent advances. One way in which this metal ‘printing’ typically happens is a process very similar to welding, where a ‘printhead’ functionally identical to a welding power supply is raked across a print area, progressively adding more metal throughout the process to yield a result. While this technique already exists at a macro scale, advances are regularly made to allow progressively smaller-scale prints using metal in additive manufacturing, including novel applications using lasers to melt very small amounts of metal at a time to generate extremely precise results.[10] Ceramics are also seeing new uses, including medical, due to the use of additive manufacturing to quickly create detailed, custom objects and models with little to no advance notice of specific requirements outside of size and material.[11]

These advances, however relevant, have yet to yield any commercially-available printer focusing on flexible materials. Most printers which are custom-built with the intent to print non-standard materials, utilizing resources provided through the Soft Robotics Toolkit,[12] exist in order to create flexible robotics[13] and medical devices. One very common material used in flexible robotics, silicone, is an unfortunately difficult material to manufacture with additive techniques.

Traditionally, silicone products are manufactured using either extrusion or molding,[14] techniques which combat the primary weakness of silicone as a material. Utilizing 'traditional' manufacturing techniques typically means that the silicone material can be all fully prepared and ready for shaping at once, which streamlines production. As this[15] patent describes, silicone is often a complex liquid mixture, often in two parts, which once finalized and mixed sets into a flexible, rubbery solid very quickly. Because of this, any silicone 3D printing system must include an external assembly which stores, measures, and pumps a specific mixture, and in all likelihood the final mixing of the two parts should happen as near to the time and location of material placement as possible. Because of this, an existing twin-syringe variable-speed pump assembly can (and must) be used in any printer utilizing silicone as a print material. Any individual interested in soft robotics customer would likely be seeking this kind of printer due to the possible gains in model creation efficiency, consistency, and ease-of-use.

These developments made in soft-material additive manufacturing techniques, then, have the potential to thoroughly democratize the study of soft robotics,[13] a field which generally exhibits lengthy development cycles due to the extended time that rapidly creating and prototyping a series of slightly-different molds for silicone parts can often take.

Silicone Printer Software Integration

Modifying a 3D printer, in this case the Anet A8 desktop 3D Printer, into a silicone 3D printer involves several steps. The software side of creating the silicone printer is extremely important. The code for the traditional 3D printer will need to be modified to accommodate the changes in its design which will allow it to operate. The silicone printer adjustment is multifaceted, and each section of the printer will involve individual software controls.

A critical aspect of developing a working silicone 3D printer is a thorough understanding of the inner workings of the software that runs each part of the printer. The base silicone printer that is being modified is an Anet A8 Desktop 3D Printer. In this project the traditional Anet A8 printer firmware will be swapped for Marlin 3D printing firmware. Marlin is the world's most popular open source firmware for Replicating Rapid Prototypes.[8] Marlin 3D printing firmware supports Arduino, which will be used extensively throughout the project. The heater assembly will need to be extensively monitored to regulate the temperature of the silicone, this will be done through Arduino code. An Arduino Uno uses C++ code and is based on a minimalist design. It utilizes an open source community allowing for the importing of many different libraries, as well.[19] The Arduino website includes a community which will be useful when encountering difficult coding issues, and how those issues translate to the development of the 3D silicone printer parts. Making coding adjustments to the basic Arduino code to operate precisely with the features of the silicone printer will be very important in developing a working silicone 3D printer. Once the code has been converted to the Arduino board it will be able to be used to operate the printer head, the heater assembly and may also be used in the pump and cartridge assembly.

Designing and creating parts to upload to the 3D silicone printer and printed requires the use of several programs. For this, SolidWorks will be the primary 3D design software. After creating an .stl file for the model in SolidWorks, it must then be converted into g-code commands.[21] To do this, the program slic3r will be used. This will allow for any necessary adjustments through the included features such as multiple extruders, brim, and microlayering.[16] After Marlin has been installed the 3D printer controller software Pronterface will be used to control motors of the 3D printer in the x, y, and z directions.[21] Pronterface includes many useful features that will be necessary to complete prints and is integrated with Slic3r for an easy user face experience.[20]

The software used in this silicone 3D printer will be crucial to the success of the project. The silicone printer is broken up into several components; the 3D printer base -- which will run on Marlin and integrate several other programs for the most useful and adaptable controls, the silicone extruder -- which will be temperature controlled and need precise coding to maintain ideal settings, and the pump and cartridge -- which will also need software modifications.

Design Description

Summary of Design

The focus of this design involved the development of a silicone 3D printer which will print cervix samples to specific functional requirements. The design of the printer, visualized in Appendix C, Figure 9, consists of the Printer Base, Printer and Printhead Modifications, the Heater Wings, and the Independent Pump Base.

The printer base subsystem was a largely-stock Anet A8 PLA/Filament 3D printer which was modified for the purposes of this project. This included replacement of the printhead, attachment of heater wings subsystem, and connection to the independent pump base. In terms of subsystem action items, the printer was assembled, powered on, and its range of motion was compatible with all modifications and attachments, which was completed.

All printer modifications, as seen in Appendix C, Figure 8, included a new 3D printed extrusion tip and mixer. The purpose of this addition was to allow the separate material streams of the silicone two-part mixture to fully mix and combine before being extruded through an all-new tip to ensure material uniformity and print quality.

The heater wings subsystem comprised of two milled aluminum blocks, fans, silicone seals, cartridge heaters, and thermistors, as well as a bulk of this project's custom wiring, and was mounted alongside the new printhead. This subsystem had the intended function of expediting the print drying process, ensuring uniform print quality, and adhesion of each layer to the previously printer layer. A very low air flow rate was intended to generate maximum convective heating while not disrupting the flow of material from the printhead. Unfortunately, this subsystem fell severely out of our fields of expertise and was only ever half-functional, due to malfunctioning components which were misdiagnosed until it became too late to fully replace them, and the relevant FRs to this subsystem were not fully tested.

The independent pump base, the largest, most unexpected subsystem to this project, was meant to replace a commercial syringe pump system that was promised, and this subsystem was not anticipated to be a fully custom fabrication. This subsystem is pictured in Appendix C, Figure 10 for visual reference, with a system chart description visualized in Appendix C, Figure 11. Effectively, the pump base was meant to depress two medical syringes full of fluid at extremely precise, even rates in order to guarantee a 1:1 (within reasonable error) mix of two substances entering the printhead. While much was completed within an unexpectedly tight timeframe, this subsystem was also never fully tested for relevant FRs against a benchmark, comparable commercial system due to availability and time constraints.

Silicone Pump System

The pump system is an integral part of the 3D Silicone printer design, since it supplies the printer with a steady stream of highly viscous silicone. The pump dispenses silicone through two 60 mL syringes mounted on a frame. Typical products that perform this function, such as the NE-4000 Programmable 2 Channel Syringe Pump, sell for approximately $1000. These pumps are medical grade and the cost is beyond the budget of this project. The design used in this 3D Silicone printer consists of a powerful stepper motor attached to a ball screw via a coupler, manufactured by the team. The ball screw is then mounted to a laser cut steel frame and operated by an Arduino Uno and easy driver, as seen in Figure 1 below. This system, while bulkier than a medical grade pump, permits more customization using the Arduino board and is significantly less expensive.

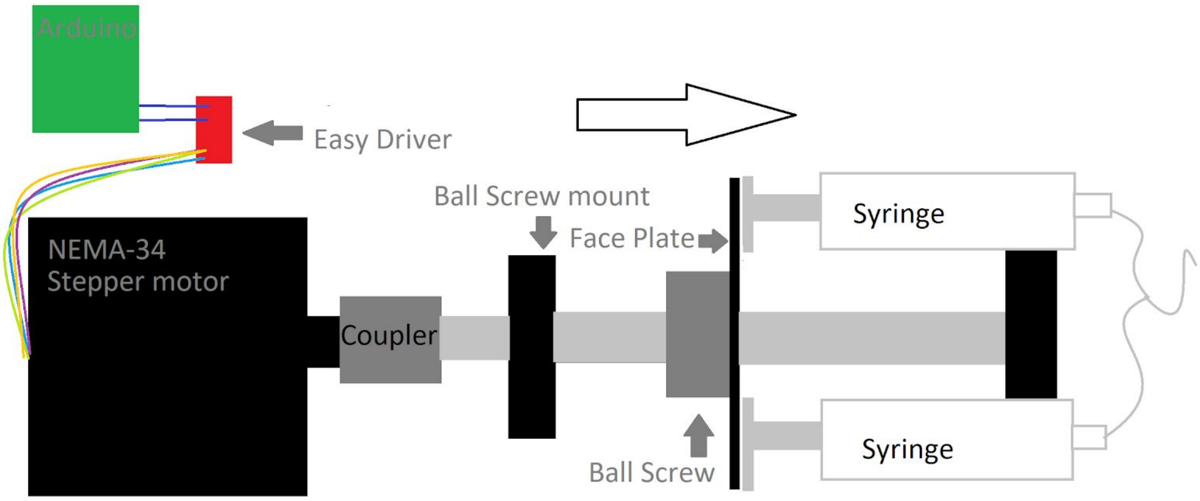


Figure 1: Diagram of pump system

Silicone is a viscous fluid and requires the application of significant force when pumped through 60 cm of medical tubing. Each syringe requires an average force of approximately 300 N to consistently dispense silicone through the tube to the printer head. Designed with a significant safety factor -- approximately 3.4 -- to ensure consistent pump speed, the pump uses a Nema 34 stepper motor and a SFU1605 300 mm ball screw kit. The motor has a step angle of 1.8 degrees, a holding torque of 4.5 Nm and a shaft diameter of 14 mm. The 300 mm ball screw kit has a thread density of 40 cm, an approximate coefficient of friction of 0.2 and a pitch diameter of 6 mm. Inputting these numbers into Equation 1 results in a force output of approximately 3500 N, which is sufficient to push both syringes.

$$\boldsymbol{F} = \frac{2 \cdot \tau(\boldsymbol{L}+\boldsymbol{u}\cdot\pi\cdot\boldsymbol{D_M})}{\boldsymbol{D_m}(\pi\cdot\boldsymbol{D_m}-\boldsymbol{u}\cdot\boldsymbol{L})} \qquad (1)$$

Table 2 shows the total cost of this pump system and compares it to the cost of the previously mentioned NE-4000 Programmable 2 Channel Syringe Pump. The total cost reduction in using this design over purchasing the medical grade pump is $800.79. This savings enables broader use and potential modifications to other aspects of the printer if the system is to be reproduced by other groups.

Table 2: Cost savings analysis of pump subsystem fabrication

NE-4000 Programmable 2 Channel Syringe Pump	**$ 950.00**
Stepper Motor	$ 40.01
Arduino Board & Easy Driver	$ 32.00
Ball Screw Kit	$ 57.20
Machined Aluminum (for case and coupler)	$ 20.00
Total	**$ 149.21**
Total savings:	**$ 800.79**

An Arduino board was connected to an easy driver which controls the bipolar stepper motor and code enables the motor to move at the desired speed. The Nema 34 is then connected directly to the ball screw which is 300 mm in length. This ball screw track is long so the case is designed specifically to enable the syringes to be pushed to the proper length without issue. The custom design of this system reduces the price of the entire project to well below $1000.

The Arduino code used to operate the stepper motor is shown in Appendix B. The quantity of steps per revolution is obtained by dividing 360 degrees by 1.8 degrees given by the NEMA 34, which is 200 steps per rotation. This code can easily be adjusted to increase or reduce the speed of the stepper motor, thus increasing or decreasing the release rate of the silicone from the syringes enabling the material properties of the final printed silicone print to be adjusted.

The ‘rotate’ function in line thirteen consists of two integers, the first indicates the number of steps while the second indicates the delay between steps. The first rotate function reads ‘rotate(-1846*(40), 1);’. The pump system requires 26 mL per hour or 13 mL per hour per syringe. When all calculations are completed this translates to one stepper motor rotation every 52 seconds. One rotation every 52 seconds means a delay between each step of 0.8666 seconds which can be seen in the code written in microseconds. The “-1846” represents how many steps occur in 60 seconds with a counterclockwise rotation. This enables a print to be controlled easily by print time. This code is intended to turn the motor counterclockwise for 40 minutes before it reverses.

The pump system is critical to the overall function of the silicone 3D printer. The pump dispenses silicone through two 60 mL syringes mounted on its frame. The design of this pump was necessary to reduce the price of the 3D silicone printer project. This pump system consists of a powerful stepper motor attached to a ball screw all mounted to a machined aluminum frame and operated by an Arduino Uno. Although this system is bulky it is simple, efficient and cheap.

Pump Base Design Description for Silicone Extruder

The pump base stabilizes the stepper motor and screw drive to effectively transmit rotary motion into linear movement. Without effective stabilization, force losses can occur, putting more stress on the motor which can lead to overheating or insufficient material flow rates to the print head. The main considerations when designing a base are ensuring that the components of the pump are stable, applying sufficient damping to the motor to prevent vibrations, and allowing all components to move freely and effectively. This base seen in Figure 2 below is designed to secure a 4.5 N-m stepper motor and a screw drive system that will move the plungers of two syringes and dispense silicone into the print head. Since silicone is a viscous fluid, the base will need to withstand significant static forces during operation. For this reason, strength and stabilization considerations must be made.

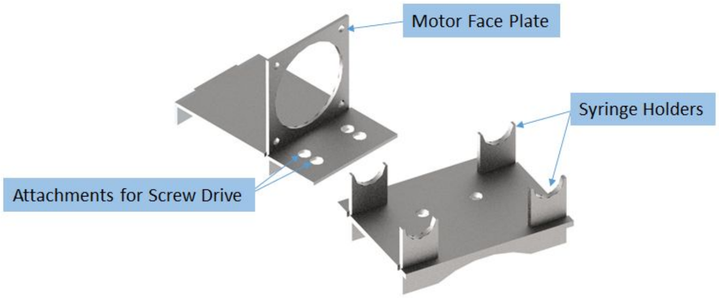


Figure 2: Overview of pump base design

The base of the pump is designed to be laser cut out of sheet metal and then welded together in order to withstand the stress applied to the syringes to effectively pump silicone through them. From calculations, approximately 300 N of force are needed to dispense silicone out of each syringe and down the length of a plastic tube and into the print head. Steel is favorable over other metals due to its high strength and rigidity. These characteristics keep the pieces of the pump stationary, mitigating any loss of force. Figure 3 shows the results of a stress analysis that was performed in Solid Edge. The piece shown holds the syringes and is subjected to the most stress in operation because the faceplate-ball screw connection pushes directly onto the syringes held in this apparatus. The syringe holder is to be fixed at the two points where it connects to the main base, which was accounted for in this analysis. A 500 N force was then applied to the each of the two holders at the point where the back of the syringe is inserted. This overestimation adds an additional safety factor to the simulation to design the holder to the maximum it would be subjected to. Figure 3 also indicates where the points of greatest stress are, near the base of each holder. This simulation also confirms that steel is a viable material option.

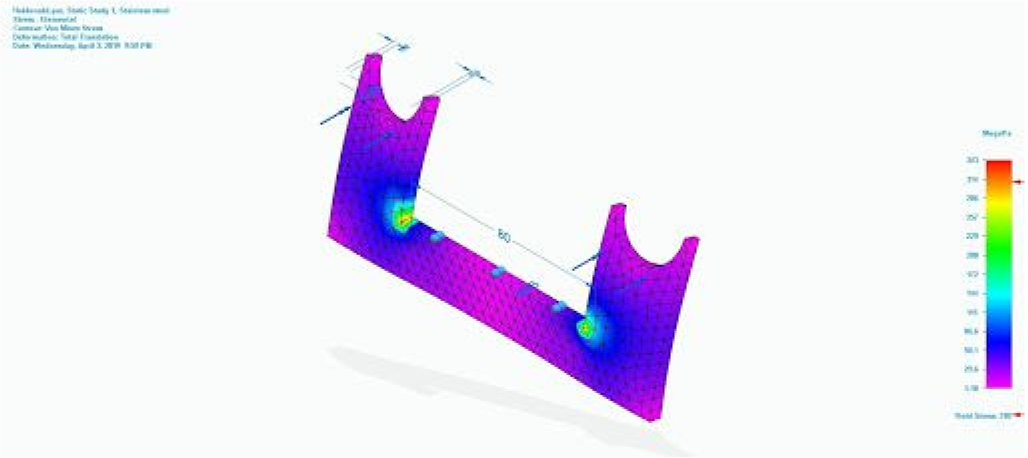


Figure 3: Stress analysis of syringe holding bracket

One key feature in the base design is the lack of a fastener for the syringes on the syringe holder. The overall purpose of the holder is to secure the syringe such that all force from the motorized screw drive can be transferred to pump silicone effectively. The ability to include this feature can be attributed to the direction of the applied force from the stepper motor onto the syringe, and thus onto its holding piece. If the syringe is placed correctly, meaning that both finger supports are supported by the holder, the syringe should not slip. Figure 4 shows the intended positioning of the syringe into the holder.

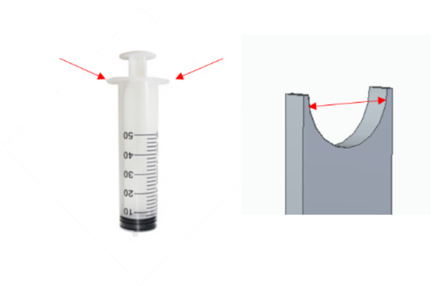


Figure 4: Syringe holding bracket with indicated placement of finger supports

In order to hold and stabilize the components of the pump, the main considerations include providing the right connections to fasten the stepper motor and screw drive fasteners. For the primary base design, screw holes are included in order to secure the additional components. The screw holes that align to the motor are designed to accommodate the design for a Nema 34 CNC stepper motor. The intended alignment can best be seen in Figure 5. Additionally, a through-hole was added for the stepper motor shaft that is intended to provide the proper clearance for the rotating components of the pump. This through-hole was over-sized in order to accommodate a shaft coupler and to ensure no interference occurs during operation.

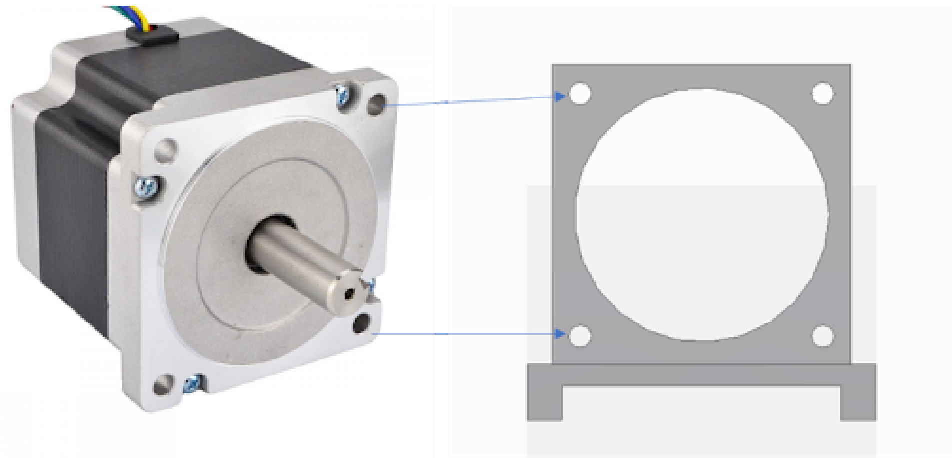


Figure 5: Alignment of base to stepper motor

The base is designed to bolt to the pump components to provide the most stability and prevent unwanted vibrations between pump components. Similarly, the main base is connected to the syringe holder with the same connections for simplicity. With a stable base, the pump can operate efficiently and the silicone extrusion can be completed successfully.

Evaluation & Testing

A combination of methods were utilized in the testing of the 3D silicone printer and each of its subsystems. A crucial element of the evaluation and testing methods used was troubleshooting individual subsystems. Figure 6 displays the troubleshooting method utilized for the Arduino and circuitry problems encountered. The fans and heater wings comprise a major subsystem of the printer, one that never became fully functional despite a large number of troubleshooting attempts. The electrical wiring element is the suspected reason for the lack of functioning fans and heater cartridge. Despite efforts to solder and re-solder the wiring of these

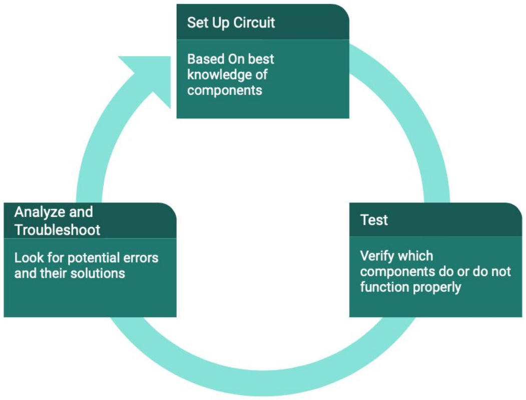


Figure 6: Troubleshooting pathway for arduino and circuitry

components, only one of the cartridge heaters began working. Originally, one heater was functioning but only because the circuit was shorting and even still, it was heating up past the desired temperature. Once the short was corrected, the cartridge heater on the left side of the printer began reading the appropriate temperature, but not the heater on the right side. While the heater cartridges were undergoing troubleshooting, one of the group's goals was to change one variable at a time. This was done in case the cartridges both began working properly so the team could identify the issue at hand. That final functional step, unfortunately, was not reached. A similar approach was taken to troubleshooting the fans. The team members in charge of this process tried altering the Arduino code in case it was referencing the incorrect pins, but that was not the case. It was concluded that either the electrical wiring, again, was the culprit or that the fans were damaged or faulty.

The pump alternative, designed and manufactured by the team, was not originally anticipated in the completion of this project. It was not until it was determined that medical grade pumps were too expensive for the given budget, that it was realized an alternative was necessary. In order to test and evaluate this subsystem of the printer system, a CAD stress analysis was performed on the base structure (see Figure 3). Once this analysis was completed, the team reevaluated the design and proceeded to design each base piece in AutoCAD so that it could be laser cut from ⅛" steel. Once the base pieces were cut and welded together, these welds were tested by running the whole pump system. Since none of the welds failed, the base was considered to be in its final form and successfully completed.

The code for the pump subsystem was also tested and debugged multiple times. The Arduino code used to power the stepper motor was a generic code uploaded from the Internet and edited as seen fit by the pump design lead. There was an issue with the code causing the faceplate pushing the syringes to reverse directions after too little time had passed. The code was then fixed to maintain force in the forward direction for long enough to complete the print before reversing and removing the pressure from the syringes. Another issue encountered with the pump was originally not having enough force to push both syringes with the silicone components inside. This issue was fixed by connecting the system to the 12V power supply.

Despite the minor issues encountered with the alternative pump system, a functioning pump was ultimately manufactured, tested, and used to create a baseline silicone test print.

Testing Silicone Material Properties

Prior to 3D printing the silicone cervixes, the ultimate goal of this 3D printer, it is important to test the mechanical properties of the 3D printed material. The current hypothesis is that the materials will have similar material properties but the following test procedure is necessary to determine whether or not that assumption is correct. If it is indeed a correct assumption, the 3D printed silicone cervixes will be sufficient replacements for the molded silicone cervixes for testing medical sutures. If the difference between the Young's modulus of the 3D printed silicone and that of the molded specimen is less than 20%, the 3D printed material will be deemed an acceptable alternative to the molded silicone. The tensile testing machine, pictured in Figure 7, would have been used to determine the stress, strain, and Young's modulus of the silicone, had a sufficient and consistent print capacity. In order to begin the tests, three

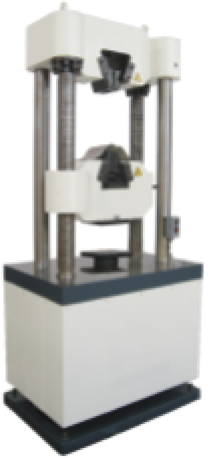


Figure 7: Standard tensile strength test machine

sample specimens of each variation of silicone, six samples total, with dimensions of 6” x 1” x 0.25” should have been created through molding and 3D printing.

To obtain the molded specimens with these dimensions, it was necessary to first design a plastic mold in SolidWorks or Solid Edge that was printed with a standard 3D printer. Once the mold was printed, it was sprayed with a non-stick spray to prevent the silicone from sticking to the mold. The silicone components were mixed using a 1:1 ratio of materials. The molded silicone strip took two attempts to successfully complete. On the first attempt, the materials were combined in a cup and the cup was placed into a vacuum to remove air bubbles. Removing air bubbles is an extremely important step in this process because imperfections in the samples may lead to issues in the tensile testing, such as premature failure which leads to inaccurate data. The problem with removing air bubbles before the mixture was in the mold was that the mixture set too much in the cup, so air bubbles were reintroduced when moving the mixture into the mold. For the second test strip, the mixture was placed right into the mold and then placed into the vacuum to remove as many air bubbles as possible. This second method worked much better in terms of removing as many air bubbles and imperfections as possible.

To create the silicone 3D printed specimens, the constructed silicone printer was used in conjunction with a CAD design of the sample with the dimensions specified above. As is the case in creating the molded specimens, it is crucial to make sure there are no air bubbles in the sample to avoid premature failure. The goal of testing the specimens with the tensile machine was to stretch them to failure. This step was not completed, however, because a sufficient enough 3D silicone test print has not yet been obtained. Had both types of test strips been successfully obtained, a computer synced with the tensile testing machine would have measured and plotted the stress vs. strain of the material. The goal was to have three samples of each type of silicone sample tested, so the average of the Young's moduli for each type of sample would have been taken. The results of this analysis would be compared when making the final determination as to whether or not the 3D printed silicone is a sufficient alternative to the molded silicone in terms of creating silicone cervixes that will be used for test sutures.

Summary and Recommendations

The assembly and integration of the 3D silicone printer subsystems was predominantly successful and the results of the design and manufacturing of the pump alternate system were very favorable. The printhead, mixer, and pump successfully interacted to extrude silicone from the syringes onto the print bed. Despite lack of assistance from the heat wings in helping the silicone set, the test prints were a good initial step in working to eventually generate a successful silicone test strip. Testing the silicone properties according to the method described above in the "Testing & Evaluation" section was not accomplished this semester, but is something that can be done and would provide useful information once a viable 3D silicone test strip is obtained. This step would allow analysis as to the reliability and usefulness of the silicone 3D printer as a substitute for creating molded silicone samples, especially as a substitute for creating molded silicone cervixes. Following design and fabrication, several recommendations can be made in order to improve the efficacy and efficiency of the 3D printed silicone printer. These recommendations, if followed, aim to address the weak points or shortcomings of the design as described in this report.

When creating silicone materials using molds, one method of affecting the properties of the silicone is by using a thinning agent to decrease the density and improve the flexibility of the solidified silicone. The incorporation of a thinning agent is a novel concept for 3D silicone printing because it expands the range of possibilities of what can be printed. The thinning agent is typically not incorporated until the two parts of the silicone mixture have already been combined, so some method of applying this process to this design should be considered. One possible method would be to add a small stepper motor controlled by another Arduino Uno that would act as an expansion to the current pump. A new base would need to be made to incorporate the new motor and an additional ball screw. Additionally, the print head would need to be redesigned in order to accommodate a third syringe. Although extensive, this would ensure full control over the release of thinning agent into the print head at a rate independent of the other two syringes to allow for more flexibility and control over print quality.

The components of this printer could also be made more aesthetically sophisticated. This design has primarily considered functionality over neatness and cosmetics, so some work should be done on this front to create a better overall device. One idea for future consideration would be machining a larger printer housing that holds the main printer, the pump, and the electrical hardware for the heater wings. The current design is very difficult to move, since there are many loose pieces that could easily fall apart if the printer needs to be moved. A housing to incorporate all of the hardware and wiring of the printer would solve this problem and also greatly reduce the overall weight of the printer. In the interest of time and ease, the pump base was made from laser cut steel and then welded together. This part of the design, while inexpensive and quick, is very heavy and takes up a large amount of space. A more clever, vertical base that could be incorporated into the printer housing would decrease the footprint of the printer significantly. Some parts may still need to be made out of steel because of its favorable strength characteristics over acrylic.

Finally, safety and improved reliability should be improved in the design as well, especially for the electrical components. In this design, the 12 Volt supply for the heater wings circuit is wired straight from the printer. While convenient, it would be best to either use a different power supply for the heater wings, or find a way to control the power to that circuit so that it does not turn on when the printer turns on. This consideration is simple, but important. To address this, a switch or on/off button could be added to open and close the circuit. This would have been very helpful when troubleshooting the heater wings circuit because the only way to reset the circuit if something were to go wrong was to unplug the entire printer, which became inconvenient over time. The same could be done for the pump, as well, to allow for easier troubleshooting. The addition of an LCD Shield for the pump would also be of value in order to make the pump more user friendly. Currently, the only way to reverse the pump if something goes wrong is to do so manually after unplugging the pump. Incorporating an on/off feature as well as a quick reverse control would make the pump much easier to use. The addition of a power distribution board would be a cost-efficient and easy way to potentially address the currently uneven distribution of power over the entire printer system and its subsystems, as well.

These recommendations serve to further progress the achievements set forth in this project. Silicone 3D printing can have a variety of applications for medical testing and clinical usage in the near future. The ability to successfully 3D print flexible material would expand the capabilities and manufacturability of silicone, providing a simpler method for creating more complex designs. Further research into this field would provide insight into these capabilities and set the course for the usefulness of this technology for years to come.

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Appendix A: Functional Requirements

Functional Requirement	Design Parameters
Printing speed	Perform within 20% to print model in ‘normal’ print materials (PLA, etc.) 5.654-6.911 mm^3/sec
Silicone Mech. Properties	Perform within 20% on spec of molded parts ~4-6 Hours to set, Determine mold mech props
Printing Dimensions	Print using ~100% of original 3D printer design print volume 220 x 220 x 240 mm
Pump replacement	Precisely and consistently release silicone mixture to form accurate mechanical properties consistent with medical grade pump
Decrease Solidification Time	Use Heater Wings Assembly to add heat to the silicone mixture after extrusion

Appendix B: Stepper Motor Arduino Code

```
int smDirectionPin = 2; //Direction pin
int smStepPin = 3; //Stepper pin

void setup(){

  pinMode(smDirectionPin, OUTPUT);
  pinMode(smStepPin, OUTPUT);

  Serial.begin(9600);
}

void loop(){
  rotate(-1846*(40), 1 ); // 1600 is one rotation  REPLACE THE (1) with however
many minutes the print is (Max 60 to replace pumps)
  delay(5000);
  rotate(1846*(40), 1000);
  delay(5000);

}

void rotate(int steps, float speed){


  int direction;

  if (steps > 0){
    direction = HIGH;
  }else{
    direction = LOW;
  }

  speed = int(1/speed *8666666); // Important: This is in microseconds
  steps = abs(steps);

  digitalWrite(smDirectionPin, direction);

  for (int i = 0; i < steps; i++){
    digitalWrite(smStepPin, HIGH);
    delayMicroseconds(speed);
    digitalWrite(smStepPin, LOW);
    delayMicroseconds(speed);
  }
}
```

Appendix C: 3D Silicone Printer Images

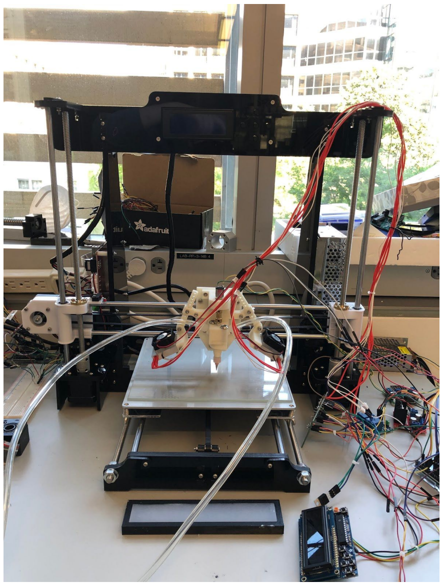

Figure 8: 3D silicone printer

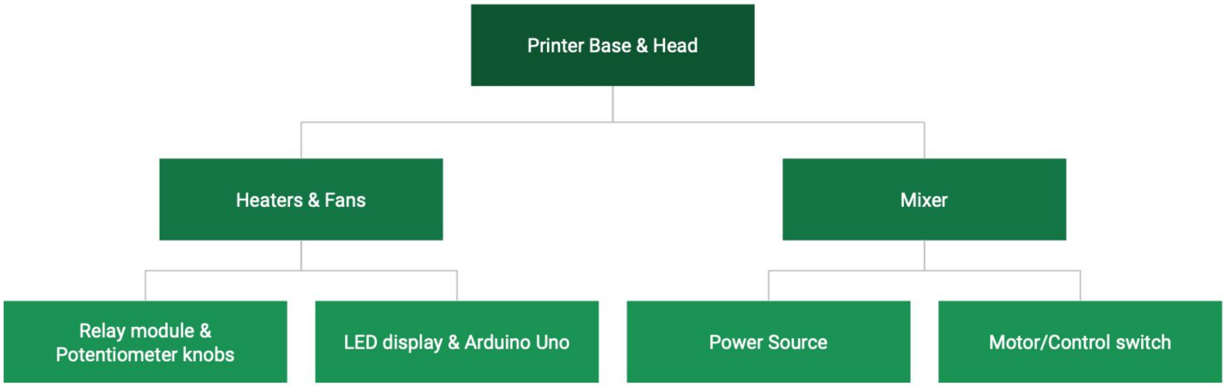

Figure 9: 3D silicone printer breakdown