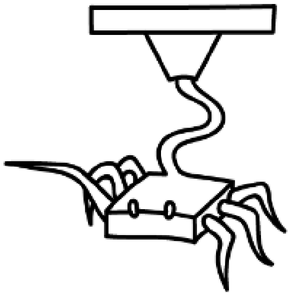

Machines Building Machines

A Major Qualifying Project (MQP) Report
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements
for the Degree of Bachelor of Science

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Date: March 2023

Abstract

Advancement in the field of soft robotics depends on the ability to consistently manufacture soft components. This process is difficult since Fused Deposition Modeling (FDM) printers can print materials with a minimum shore hardness of 50A, silicone injection models do not allow for rapid prototyping, and hand-poured silicone molds are subject to human error. Silicone elastomers come in a wide variety of hardnesses, however, printing systems cost thousands of dollars, making them inaccessible for most labs. In contrast, our newly developed printhead is capable of FDM printing silicone parts by integrating with the existing E3D ToolChanger system for under $250. This print system was purpose-built in software, design, and wiring to only require an hour or two of setup and basic 3D printer knowledge. This is possible because the pump design of the printhead has one stepper motor which can be commanded in the same manner as the extrusion stepper on a traditional FDM printer. Despite a 10% flow rate inconsistency in our pump system, the printhead produced successful prints with similar properties to traditionally molded silicone, with a shore hardness of 00 35.

Acknowledgements

We extend our sincere thanks to Professor Markus Nemitz for his continual ideas, support, enthusiasm, and encouragement over the course of this project. We also express our gratitude to Cem Aygül for his tremendously useful ED3 knowledge, experience, and assistance. Lastly, we want to acknowledge Russell Lang in the Civil Engineering Department for allowing us to use his lab for tensile testing, and teaching us how to properly operate and pull data from the Instron. Their unwavering support, guidance, and expertise have been instrumental in achieving the success of this project, and we could not have accomplished this without their contributions.

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Material Properties	Ron
Heat-Assisted Chemical Curing	Jared
Chemical Curing with Infrared Acceleration	Ron
UV Curing	Jared
Comparison of Curing Methods	Jared
3D Printing Silicon	Elena
Niche Application	Ron, Jared
Existing Commercial Solutions	Elena
Case Study: Direct 3D Printing of Silicone Elastomer...	Elena
E3D Toolchanger	Elena
Mechanical Interface	Elena
Electrical Interface	Jared, Elena
Material Selection	Jared
Silicone Ratio Testing	Elena
Curing Speed	Ron
Tensile Testing	Jared, Elena
Accelerated Curing	Ron
Heated Bed	Ron, Elena
Infrared Lamps and Multilayer Curing	Jared, Elena
Material Comparison Conclusions	Ron, Elena
Pump Selection	Elena
Screw Pump	Elena
Syringe Pump	Elena
Gear Pump	Elena, Ron
Peristaltic Pump	Ron
Peristaltic Pump Design	Ron
Tube Selection	Elena
Mixing Nozzle	Elena
H-Splitter	Elena
Heating System	Elena
Thermal Protection	Elena
E3D Interface	Jared
Gearbox Design	Elena
Leak Testing	Elena
Manual Extrusion	Elena, Jared
Conclusions	Elena
Recommendations	Ron

Contents

List of Tables

List of Figures

Executive Summary

There is a growing need for rapidly iterable soft material prints within multiple industries. One of these fields is soft robotics, the idea of creating robots that more closely resemble a living being with a focus on flexibility rather than rigid structures. Silicone has been a major contributor to this field, however, its tedious process provides ample opportunities for human error. The development of 3D printing has provided a way to create parts without the need for human interaction during the process. The softest material that can be printed on a traditional FDM printer is a shore hardness of 50A, which was not soft enough for many flexible, stretchable, and inflatable parts. Strides have been made in 3D printing silicones, but due to the recent development of this technological advancement, existing printers are exorbitantly expensive. Precision dosing pumps could be purchased and attached to an existing printer system for $12,000 [17], and similar style pumps could be found from other retailers starting at $3,000. Extremely precise printing systems such as Carbon used SLA printing methods to cure silicone elastomers, however, their systems started at $24,000 per month. Our goal is to develop a new silicone 3D printing system at an accessible cost to increase the use of silicone printing for soft robotics and all other fields that benefit from this technology.

To print faster than molding, platinum-based silicones are the best affordable solution. FDM printing requires a quick transition from liquid to solid so that the material does not overflow and distort the print shape. Traditionally, this means that the thermoplastic is melted in the nozzle and cooled to change states to a solid outside of the printer with a fan, however, silicone starts as a liquid because its two parts have not cured together. This process is chemical meaning it can be accelerated by heat. For the purposes of this project, Ecoflex 00-35 FAST was determined as the best option for initial design due to its 5-minute room temperature cure time lower unmixed viscosity, and lower shore hardness. Integration with the E3D was a major factor in our design decisions. We chose peristaltic pumps over syringes to allow us to control the system using one stepper motor for extrusion and retraction, as well as allowing for easy silicone refilling. With all motors of the E3D as stepper motors, this makes our design seamlessly compatible for running with the existing software (SuperSlicer) and setup of the ToolChanger. For system design, we decided to use a pump system that depends upon the stepper motor for all aspects of extruding and retraction during the printing process. Given our budget, time constraints, and needs, we determined the peristaltic pump to be our best pump type. The greatest assets of the peristaltic pump are its simple, and therefore cheap, construction and continuity, meaning the fluid never switches tubes or enters into something foreign making contamination impossible. The outputs of these pumps enter a static mixing nozzle, traditionally used for epoxies, with the output of the printer at the end of the nozzle. Both a render of the system design and the final system is pictured below.

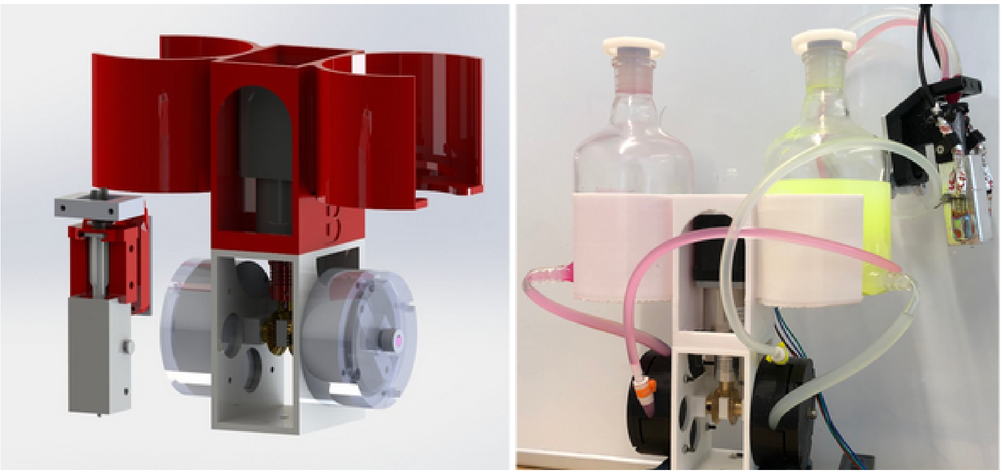


Figure 1: Render of system (pictured left) and final system design (pictured right)

After completing the system build, the extrusion process was tested to determine how consistently the peristaltic pump extruded parts A and B of the silicone simultaneously. There was a 10% difference in the weights of parts A and B, which suggested that while the prints would still cure, the material properties may differ from a 1:1 ratio. This disparity was most likely caused by slippage in the set screw connection from the drive shaft to the pump rotors but may have also been affected by slight differences in 3D-printed pump geometry. Due to this error, the material properties of our prints may have been affected, but we did not have time to fully investigate.

With team-approved testing of our system, the printhead was implemented to the E3D and printing tests were conducted. For our successful silicone prints, we measured the outside XY perimeter to be 1.3 mm greater than the CAD which makes sense since the diameter of the nozzle is 1.27 mm and the way the part was sliced, the nozzle follows the outside perimeter of the STL, adding its radius to both sides of the print. Due to the time constraints of our project, we only had time to conduct 5 printing attempts (3 of which were successful which is not enough to draw accurate conclusions on how accurately our system can print. With proper tuning after more test prints, there is potential for accurate prints that are 1:1 with the CAD model since there are no system limitations that would alter the print substantially. For material properties, the Young's modulus of the 3D printed silicone was closer to the manufacture's specified value than when a cast was filled by the printhead extrusion nozzle. However, the Young's modulus of the hand-mixed cast was slightly better than the result from the fully printed silicone, 0.149 MPa and 0.168 respectively. The reason for this discrepancy lies in some combination of improper ratio of part A and B, accelerated curing, and the mixing of the mixing nozzle. Recognizing this limitation in material property, if a user determines that the speed of producing silicone parts is more important than the accuracy of material properties when compared to the manufacturer's specifications, our system fulfills their needs.

Our print system achieved the project goals of producing silicone parts with a low overall cost. With our system totaling less than $250, this is a reasonable price for anyone who would want to implement silicone printing into their lab or company for efficient parts without the need for human interaction. When compared to the FDM printhead[10] that are designed for the E3D at $138, $250 is a reasonable price for anyone invested in FDM printing to include silicone in their printing procedures.

1 Introduction

The objective of this project was to research, design, and develop a low-cost silicone 3D printer that could integrate smoothly into an existing additive manufacturing platform, improving the manufacture of soft, multi-material printed robots. There was a growing need for manufacturing soft materials with the aid of computers in the soft robotics field. FDM 3D printers could only print soft filaments down to around a shore hardness of 50A, which was not soft enough for many flexible parts and actuators. Manufacturing silicone parts was done by casting, which is difficult to perform consistently as it depends on humans to equally mix and pour the silicone [28]. Cast parts also suffered from dimensional inaccuracies as the limits of casting often required parts to be cast in multiple pieces and glued together, leaving stress concentrations at the seams. Difficulty manufacturing consistent soft parts can be a significant problem for soft roboticists, and providing an accessible 3D printing solution could be very helpful in advancing the field.

We approached the problem of constructing our silicone printing system by defining the following requirements:

1. Can print 3D silicone structures
2. Structures are air and watertight
3. Integrates into existing 3D printer
4. Order of magnitude cheaper than current options
5. Faster than molding
6. Quick turnaround between prints (minimal clean-up)
7. No human intervention is necessary during print

We had about six months to complete the project, and a budget of $750. These constraints lead us to prototype and iterate quickly to develop a viable design that would produce quality parts. As we needed to cut costs, we identified that the pumps were the most expensive component in the system and endeavored to make them cheaper. Since highly precise pumps were very expensive, we conducted experiments to determine how error in the 1:1 ratio of silicone parts would affect the material properties. We compared the quality of our prints by printing tensile samples and comparing them to their hand-cast counterparts. These experiments showed that our prints were functional, but could be improved by increasing the precision of our pumping system.

There have been several solutions to the problem of 3D printing soft materials, however, they are extremely expensive. Precision dosing pumps could be purchased and attached to an existing printer system for $12,000 [17], and similar style pumps could be found from other retailers starting at $3,000. Extremely precise printing systems such as Carbon used SLA printing methods to cure silicone elastomers, however, their systems started at $24,000 per month. These price points make printing silicone inaccessible for most soft robotics labs, and out of the question for hobbyists or startup companies. A group of roboticists at Oregon State University developed a silicone printer with similar constraints [28], however, we decided to improve on their design by making the system easier to clean, refill, and reduce downtime between prints.

2 Background

Silicone comes in many forms, with a variety of different material properties. We examined what types of silicone would be most relevant for this project, and how they perform. One of the primary differences between types of silicone elastomers is the curing reaction. Some types of silicone cure faster when exposed to heat, while others cure when exposed to ultraviolet radiation. We also examined existing solutions for printing silicone.

2.1 Silicone Elastomers

In its elastomeric form, silicone is very useful for soft robotics due to its elasticity and durability. This type of silicone can be cured with several methods, determined by additives that cause cross-linking to solidify the material. These additives can also facilitate accelerated curing, which we used to enable layering in our prints. FDM printing requires a quick transition from liquid to solid so that the material does not overflow and distort the print shape. Traditionally, this means that the thermoplastic is melted in the nozzle and cooled to change states to a solid outside of the printer with a fan, however, silicone starts as a liquid because its two parts have not cured together. This is a chemical process which can be accelerated with the addition of heat. We compared several types of silicone elastomers and decided to use a platinum-cured, 1:1 mixture due to its low cost, and ability to be cured faster when exposed to heat.

2.1.1 Chemical Properties

While silicone can take many forms, from liquid lubricant to solid rubber, the most useful form for soft robotics is a soft, rubbery elastomer. Scientifically known as "polysiloxane," silicone consists of a chain of Silicon and Oxygen bonds, with organic groups attached to this framework, shown in Fig 2.

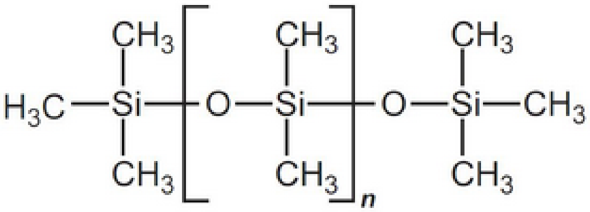


Figure 2: Polysiloxane structure [20]

Silicone elastomers are thermosets, meaning they cannot be melted once they have been fully cured. These properties are achieved with additives such as tin or platinum which cross-link, creating a three-dimensional network of chains. The more crosslinking occurs, the harder the material will become [20]. Inside the polymer chain, the silicon-oxygen bonds are more stable than those of organic molecules, which gives silicone its unique resistance to UV exposure and oxidation. This stability is desirable because it prevents silicones from reacting with most chemicals, although it is still susceptible to damage by strong acids and bases [1],[21]. Because silicone is a thermoset, it cannot be recycled like traditional thermoplastics used for 3D printing applications. While silicone takes 50-500 years to break down in a landfill, it does not produce microplastics [26]. This lack of biodegradability makes silicone a popular candidate for parts that require bio-compatibility.

2.1.2 Material Properties

Silicone is used in a multitude of industries and purposes due to its unique and beneficial properties. Silicone has excellent thermal stability from 316 °C at the high end and remains flexible until -51 °C

[1]. Silicone's resistance to water, UV light, oxidation, compression, shear, and fire makes it suitable for application in nearly any environment, while its biocompatibility makes it safe to use in human/medical applications. It is an electrical insulator, sterilizable, food-safe, and has many color and translucency options.

The properties that make elastomers beneficial for soft robotics are its ability to stretch and hold air pressure. The study shown in Fig.3 used samples 3mm thick, 7.5mm wide, and 33mm long to determine the uniaxial tensile stress vs. strain curves for 17 silicone elastomers commonly used in soft robotics [25]. These trials included the Smooth-on product Slacker in certain mixtures, which makes the material softer and more "flesh-like". The addition of slacker can also make the cured silicone slightly tacky [22].

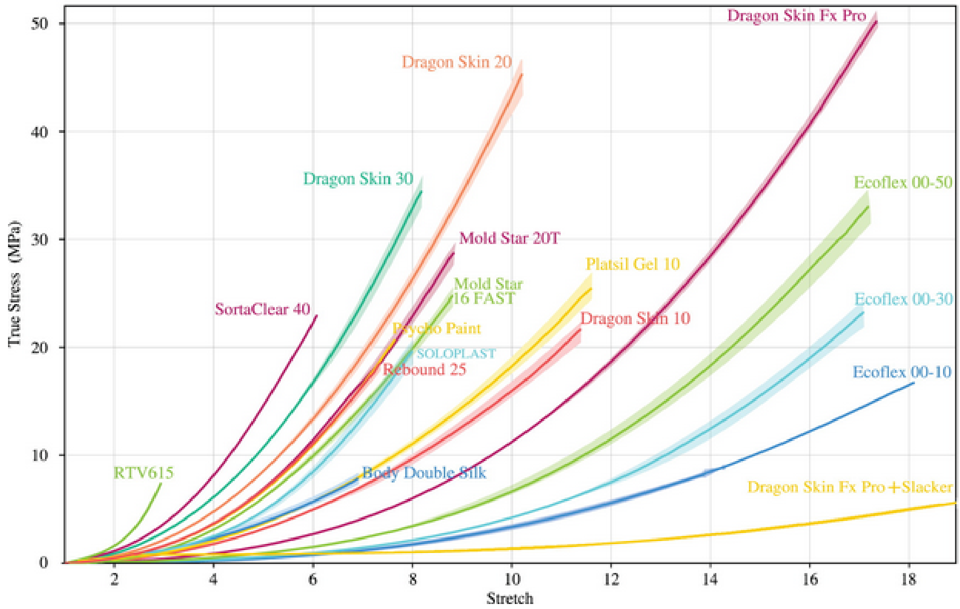


Figure 3: Uniaxial Tensile Stress vs. Stretch Curves of Silicone Elastomers

2.1.3 Heat-Assisted Chemical Curing

To initiate the curing process, a catalyst must be used to begin the chemical reaction. Silicone curing can be enabled with the addition of either a tin or platinum catalyst. Tin does not respond as dramatically to external heat, relying on additional reactants (such as an increased amount of catalyst) to decrease cure time. Part thickness then becomes a key factor, the thicker the product the slower the temperature increase. Externally increasing process temperature while using a platinum catalyst will increase the cure rate. Roughly for every 10C, the cure rate could be increased by 20-25% [21]. Temperature build-up must be well controlled, otherwise the risk of degradation increases.

2.1.4 Chemical Curing with Infrared Acceleration

Most heat-accelerated curing is caused by an external source, however using infrared light, we could internally heat the silicone, which could either be used on its own or in combination with external heating. Adding IR light internally heats the silicone, decreasing the cure time significantly, with roughly equivalent strength as external heating (as shown in Fig. 4[11]. In this study, a millimeter-thick silicone adhesive MED1-4213 with a 24-hour cure schedule cured in 30 seconds, where iCure is using infrared curing.

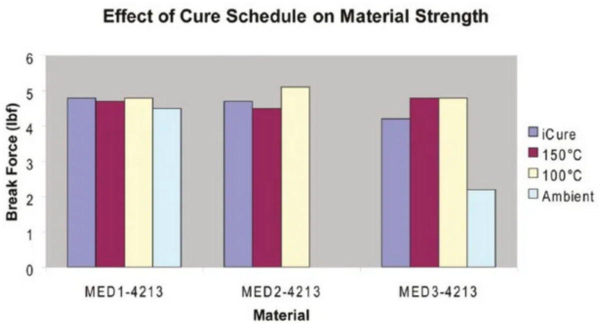


Figure 4: Effect of Accelerated Cure Schedule on Material Strength

This data suggests that heat acceleration on silicone curing should have negligible effects on the material strength of the end product.

2.1.5 Ultraviolet Curing

Technological advances have led to the rise of using ultraviolet light (UV) for silicone curing. This is a photochemical process in which high-intensity ultraviolet light is used to instantly cure or “dry” inks, coatings, or adhesives. UV formulations are liquid monomers and oligomers mixed with a small percentage of photoinitiators and then exposed to UV energy. In a few seconds, the formulation - inks, coatings, or adhesives instantly “harden” or cure, ready for the next processing step. Fig. 5 represents the UV curing process at the chemical level, with the green molecules representing the photoinitiators [12]. Some UV-curing silicones require post-processing, in the form of additional heat or UV exposure to ensure the cure is completed. However, this process is dependent on the silicone mixture chosen by the user.

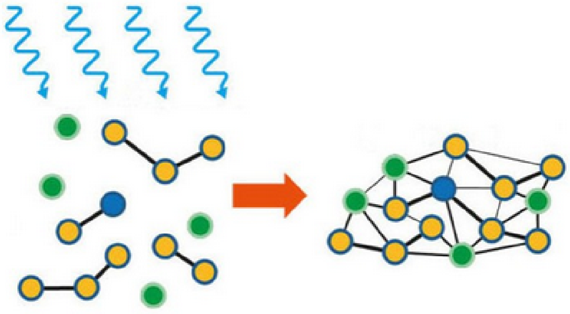


Figure 5: Molecular representation of ultraviolet curing [12]

2.1.6 Comparison of Curing Methods

With each curing process comes positives and negatives. Tin catalysts are a cheap base option and external heat is not required for the curing process which can be a major benefit. Negatives include less control over curing time and temperature than other solutions and the amount of catalyst required changes depending on how thick the silicone print is. With platinum as a catalyst, the cure speed can easily be controlled using external heat during the process. Curing this way leads to the strongest and longest life span of silicones while only having to use a 1:1 mix in the solution. The major downside is price, being the most expensive option due to silicone mixture costs.

Fig. 6 shows the largest advantage of using UV curing, the process cures as fast as platinum at 150 °C while being at room temperature [27]. However, when compared to other curing techniques the silicone is weaker and alters some properties of the silicone.

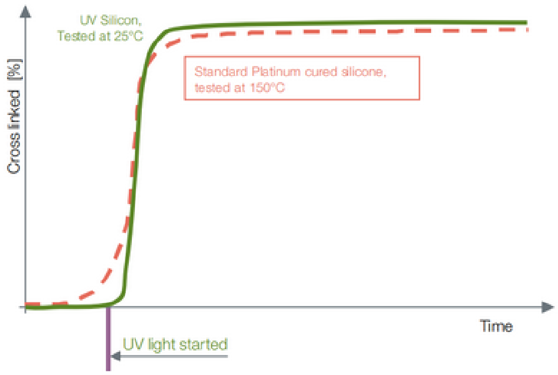


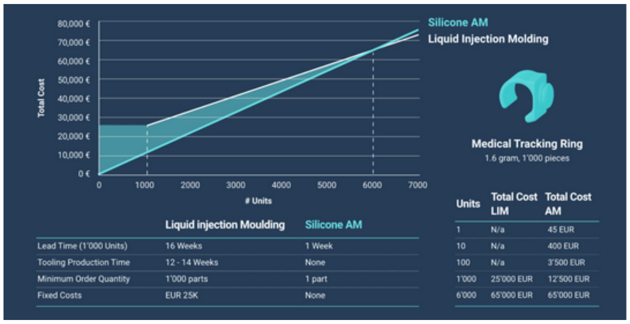
Figure 6: Molecular representation of ultraviolet curing [27]

2.2 3D Printing Silicone

Silicone parts are difficult to manufacture by hand, requiring precise mixing and pouring of the liquid mixture. This can be a lengthy process, and it is difficult to make parts consistently. The addition of 3D printing has made precision manufacturing affordable and accessible for hard plastics, however soft materials such as silicone pose a unique challenge.

2.2.1 Niche Application

3D printing allows for rapid prototyping, low-volume production, a greater level of customization, and new geometric possibilities. Rapid prototyping allows for iterative design techniques that create optimized parts. Low-volume production allows the use of parts that would previously have required the purchase of at least 1000 parts due to the initial cost of creating a mold for injection molding. This initial cost makes 3D printing silicone cheaper than injection molding until the 6000th unit [18]. Since there is no lower limit on the part count, that allows the manufacturing of unique parts. Medical devices can be made unique to the individual. Additionally, 3D printing has different geometric limitations compared to injection molding, allowing new designs and internal structures. These benefits overcome the slower speeds and worse production at scale of injection molding in certain industries, especially research and development.



	Liquid injection Moulding	Silicone AM
Lead Time (1'000 Units)	16 Weeks	1 Week
Tooling Production Time	12 - 14 Weeks	None
Minimum Order Quantity	1'000 parts	1 part
Fixed Costs	EUR 25K	None

Units	Total Cost LIM	Total Cost AM
1	N/a	45 EUR
10	N/a	400 EUR
100	N/a	3'500 EUR
1'000	25'000 EUR	12'500 EUR
6'000	65'000 EUR	65'000 EUR

Figure 7: Silicone manufacturing times [18]

3D printing of silicone is a newer technology on the market, even with this short time, there are many places where this development can influence multiple industries. Medical-grade silicones are used for implants, feeding tubes, catheters, respiratory masks, hearing aids, and containers in the healthcare space. Dentistry can use silicones to create soft parts such as gum models so dentists have a more realistic recreation of the mouth. This allows them to create dental devices more accurately for any patient. The electronics industry can use 3D-printed silicones to produce new designs to protect sensitive components that would be impossible or impractical using traditional methods. For on-demand prototypes and parts, this technology is an advancement in the field of soft robotics. This creates flexible components and allows researchers to make prototypes quickly for testing. Industrial markets can benefit from making seals and gasket prototypes quickly to test designs before mass printing [18].

2.2.2 Existing Commercial Solutions

One of the only commercially available silicone printers is manufactured and sold by Carbon. The company sells its own silicone material called Sil 30, which is UV cured and has a shore hardness of 35A. This material is compatible with their existing print systems, which start at $25,000 a year [24]. This print system may be affordable for corporations, but makes printing soft materials inaccessible to most people. As the field of soft robotics still consists primarily of academic research groups, the price point of this printer is a limiting factor for the advancement of soft robotics using 3D-printed silicone. UV-cured resin printing is also offered by Viscotech, which supplies extruders for viscous and abrasive liquids. Their printheads use a custom pump system to achieve a precise output. These pumps have been successfully used to print test samples for material characterization [15], however, they are quoted at $12,000. The cost of these products has made 3D printing silicone inaccessible without large amounts of funding, which slows the progress of the soft robotics field.

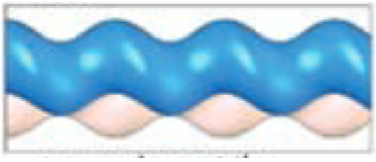


Figure 8: Endless piston pump diagram [17]

2.2.3 Case Study: Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts

A research group at Oregon State University constructed a custom silicone 3D printer and compared the performance of printed pneumatic components with molded silicone. While they concluded that the printed components performed significantly better than those that were molded, a closer look at their process suggests the need for further research. The group constructed their print head using precision syringe pumps from Harvard Apparatus to feed two-part Dragon Skin 10 Very Fast into a mixing chamber. Inside the mixing chamber, parts A and B were combined with an impeller powered independently from the pump system. The silicone was extruded through a 1.29mm nozzle onto a heated bed, and each layer was cured with convective heaters attached to the print head [28].

One notable contribution of this paper was the inclusion of the Thi-Vex viscosifying agent in the Dragon Skin mixture to help the layers maintain their shape on the print bed. Samples of Dragon Skin with and without the Thi-Vex additive were tested with a linear-shear rheometer to characterize their respective viscosities as they cured. The results of this test showed the sans-additive mixture behaved like a viscous fluid before reaching its ‘gel point’ at around 12 minutes of curing, after which it transitioned to an elastic structure. Conversely, the Thi-Vex mixture behaved like an elastic structure for the entire curing period [28]. Adding the Thi-Vex slowed down the cure speed at room temperatures, but both mixtures plateaued simultaneously at 60C. These findings suggest that adding a viscosifying agent to the silicone mixture could be beneficial in preventing uncured silicone layers from deforming on the build plate, especially in the presence of convective heaters [28].

To characterize print quality, 4-channel “tentacles” were compared with pneu-net actuators by measuring the force they exerted on a load cell when pressurized. The results of these tests showed significantly higher force output from the 3D-printed tentacles, however, this disparity was likely due to errors in the

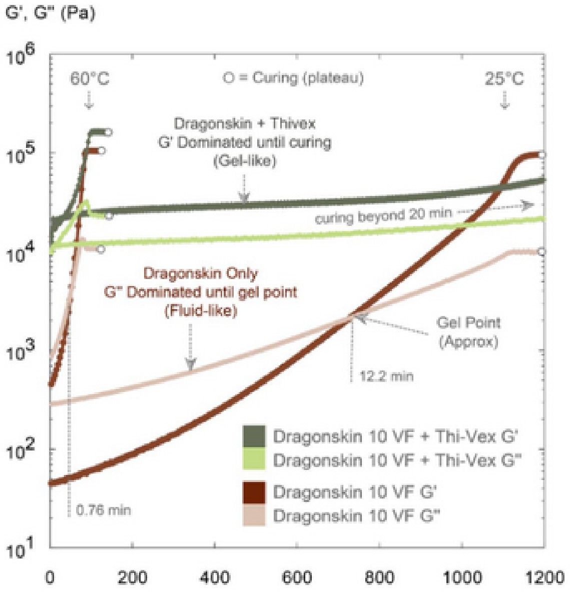


Figure 9: Viscosity behavior of Dragon Skin mixture with and without Thi-Vex viscosifying agent [28]

molding process. The authors mention dimensional inaccuracies due to the following: molding the actuators in two parts and manually laminating them together, molds expanding during the curing process, and an actuator springing a leak, being manually repaired and then subsequently used for testing [28]. If nothing else, these errors suggest eliminating the human element in soft actuator fabrication would likely produce higher-quality silicone parts. The authors hypothesize that curing a part layer by layer reinforces the walls in the same way that fabric thread has been used to buttress soft actuators [28]. Whether this effect is real or simply apparent due to the difference in fabrication quality of the samples requires further examination.

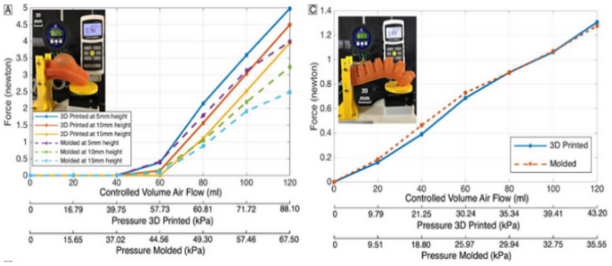


Figure 10: Measured output force of printed and molded actuators [28]

2.3 E3D Toolchanger

The ToolChanger system sold by E3D provided an excellent platform for prototyping a new printhead because it was designed to enable modular manufacturing methods. The ToolChanger has four tool mounts, which can be used to hold different FDM print heads or even subtractive manufacturing tools [10]. The system is shown in Fig. 11 Because the system was designed with customization in mind, integrating custom tools can be accomplished relatively painlessly.

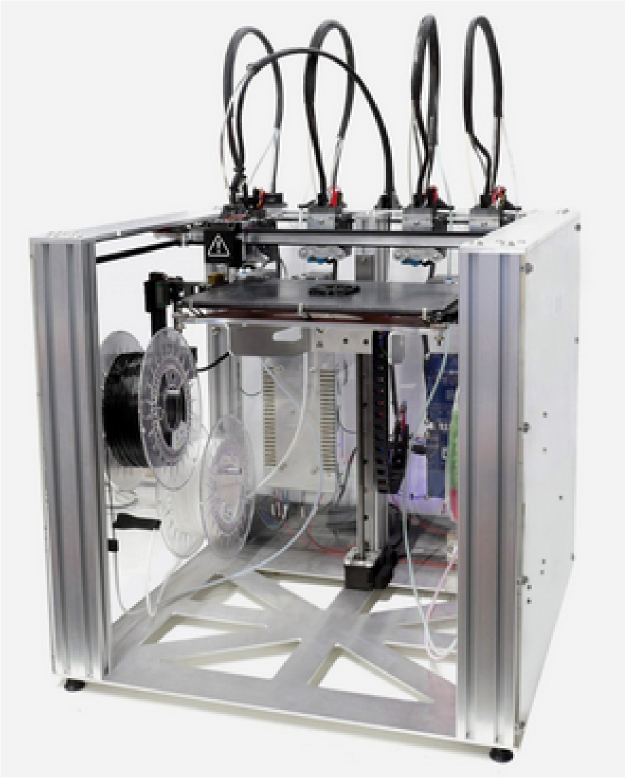


Figure 11: Image of E3D ToolChanger

2.3.1 Mechanical Interface

The E3D ToolChanger system comes with adapter kits to mount print heads to the printer, shown in Fig. 12. An adapter plate mounted to the ToolChanger uses balls and rollers to center the desired tool, and the tool is then picked up using a single rod. While there was some play in this joint, it did not appear to affect printing with the standard filament extruders. It was important to consider the weight of the extruder we designed to ensure it would not be too heavy for this connection. Print heads dock on the back of the aluminum frame, mounted on pins, and align with a magnet. The pin, slot, and magnet system is provided by E3D, and drawings are available online with precise dimensions [10].

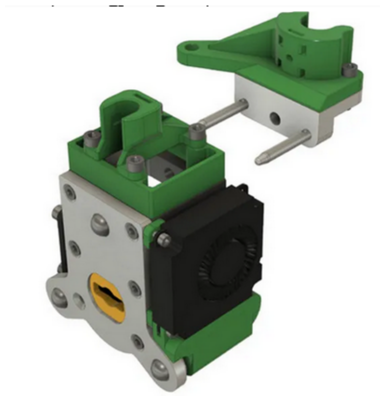


Figure 12: Example print head (green) with E3D mounting and docking hardware (gray) from [7]

2.3.2 Electrical Interface

With the customization provided by E3D, there are a variety of board options that a user can choose to create a system that best suits their needs. The main board for this project is the Duet 2 board with Ethernet, an advanced 32-bit controller designed specifically for 3D printers and other CNC machines (Fig.13). Super quiet TMC 2260 stepper drivers are utilized for motor control with up to 256 micro-stepping control [5]. Five additional motors can be implemented when using the DueX5 expansion board, equipped with 5 more TMC 2260 drivers [6]. Using stepper motors provided maximum control over motors used for any system and allowed for adjustments of any E3D tool. Connection to the board can be made via a PC, tablet, or smartphone that is on the same network, allowing for maximum control from any platform the user has available.

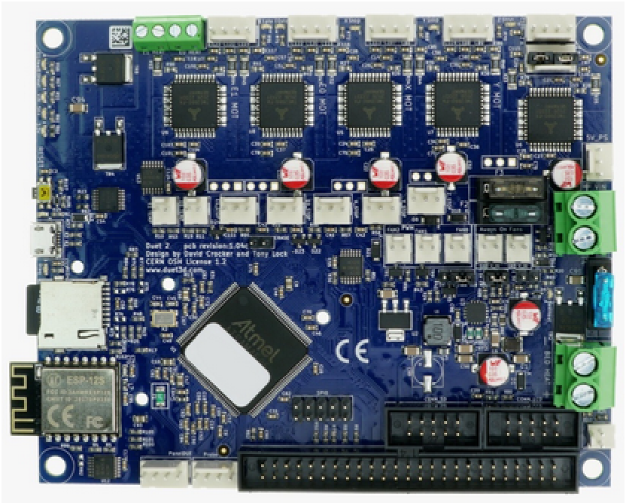


Figure 13: Duet 2 Mainboard for the E3D Tool Changer [5]

The ToolChanger system is programmed using G-code, which is standard for CNC machines. Because every machine is set up differently, the manufacturer provides a “cheat sheet” indicating the actions and related parameters for each command. Because the ToolChanger system uses G-code, it is easy to modify motions for custom print heads by adjusting the indicated offsets. G-code is commonplace in modern CNC manufacturing and should enable us to quickly make adjustments to the print system.

3 Design and Development

Our design process was centered around two major questions: which silicone elastomer to print, and what type of pumps to move it with. For both of these considerations, we needed to select an affordable option without significantly sacrificing performance. To make this determination, we investigated all of our pump options and tested out the cheapest ones. We also investigated how a difference in the 1:1 weight ratio of our silicone options would affect the material properties of the print. We decided to use Ecoflex 00-35 silicone and make our own peristaltic pumps, as that combination showed the best performance with the lowest cost.

3.1 Material Selection

When considering all of the silicone and curing options available for this project, we decided on building a system for platinum-curing silicone. Although ultraviolet curing can be accomplished at a comparable speed to platinum curing without heat assistance, the potential weaker silicone and alteration of properties raised concerns (refer to section 2.1.6 above). Using UV curing silicone does not fit the requirements of this project as this solution requires a larger financial investment from the user as opposed to tin or platinum-based curing[2]. To make printing faster than molding, platinum-based silicones are the best affordable material which can be accelerated by heat for efficient curing. For the purposes of this project, both Dragon Skin 10 VERY FAST and Ecoflex 00-35 FAST from Smooth-On were considered as material for initial testing and printing [4], [8]. Ultimately, Ecoflex 00-35 FAST was determined as the best option for the initial design due to its faster cure speed, lower unmixed viscosity, and lower shore hardness.

3.1.1 Silicone Ratio Testing

High precision pumps are very expensive, therefore we expected some variation in output from two pumps driven by one input. To determine how this might affect the curing, we varied the 1:1 ratio of parts A and B. In these experiments, we varied the ratio in both directions, with increasing percent error. We measured how quickly samples with different component ratios cured compared to a control of 1:1, and also measured their performance in an ultimate tensile test. The results of these experiments suggest that anywhere above a 5% error in the ratio of A to B will cause inconsistent curing speeds and material properties, however a larger sample size is required to determine how much of that inconsistency was caused by human error like dimensional inaccuracies with molding or inconsistent mixing.

3.1.1.1 Curing Speed

To determine how much the ratio can change without a dramatic effect on the material properties of the silicone, we ran a curing test at 9 different ratios. We wanted to test how the divergence in ratio either more A or more B affected cure time and shore hardness. To accomplish this goal we varied the weight ratio by 2%, 5%, 10%, and 20% for both parts and tested the samples every five minutes with a Shore A durometer. Fig. 14 illustrates that Dragon Skin 10 VERY FAST cure time is either equivalent (More B) or faster (More A) which means there must be more cross-linking agents in A than is necessary for curing. This was a very encouraging result for our project as, the silicone cured fully even when the ratios were 20% off, suggesting that our pumps did not need to be highly precise to produce functional parts.

We only performed curing tests with Dragon Skin 10 VF, because we had access to a Shore A durometer which is not valid below 10A, thus unable to measure the softer Ecoflex material. The cure times fluctuate when exceeding a 5% error in the weight ratio. Ideally, Ecoflex would be tested with the proper durometer, but we decided to move forward in the interest of money and time.

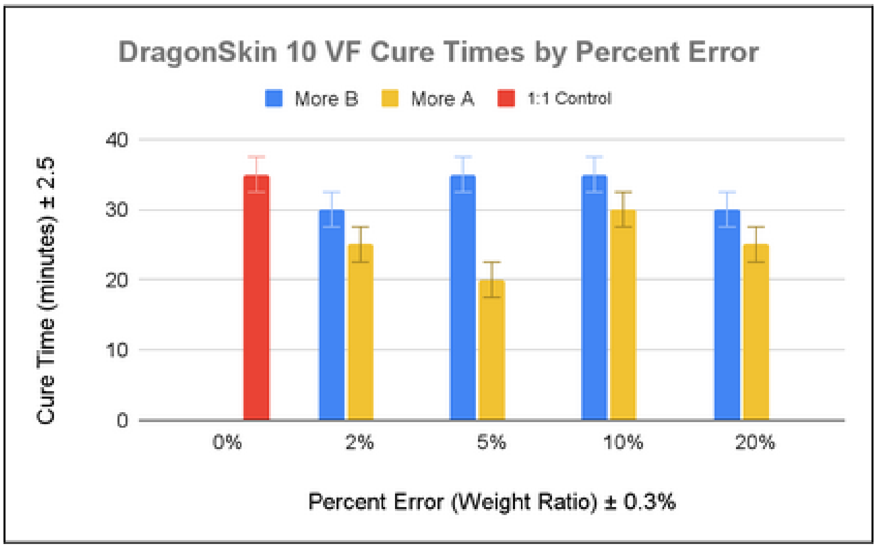


Figure 14: Time for each Dragon Skin sample to reach a shore hardness of 10A. Error bars show the estimated uncertainty of the timer

3.1.1.2 Tensile Testing

We performed tensile tests on silicone samples produced with different weight ratios to determine if a change in the weight ratio would significantly affect the material properties. This is crucial for determining how accurately the pumping system needs to output material at a 1:1 ratio. Two samples were created with 2%, 5%, 10%, and 20% more part A than B by weight, repeated for more part B than A, and two 1:1 control samples. We first tested Dragon Skin 10 VF and then repeated the steps with Ecoflex 00-35 FAST. For these tests, we used the ASTM D412 standard, which is commonly used for highly elastic materials[23]. This standard was also used by a group performing material characterization on printed silicone samples, although they used a smaller geometry of sample[15]. It is important to note that while we used the geometry specified in D412, we did not use die-cut samples for these tests as recommended. All of our cast samples were cast in a dogbone-shaped mold, which is important to consider when comparing our results to other studies.

As shown in the Fig. 15, all of our cast samples failed to reach the Young's modulus specified by the manufacturer [8]. However, we determined that this error was due to the air bubbles caused by mixing the samples by hand and pouring them into molds. The effect of air bubbles can be seen in Fig. 16 as the samples all broke in different places on the gauge length. Because these two silicone mixtures have very short pot lives, it is not possible to place the sample in a vacuum chamber to remove the bubbles before the silicone cures. The Dragon Skin samples, while stiffer than the manufacturer's specifications, were fairly consistent, and got slightly less stiff after 10%. The Dragon Skin control samples had a significant amount of variation in performance, and the error ratios showed little variation when compared to this wider range. When we compared the Dragon Skin samples engineering stress, the results fluctuated wildly after a 5% error. These results are shown in Appendix A. The Ecoflex 2% error samples were stiffer than the control, and the 5% samples had a lower stiffness. After 5%, the samples increase in stiffness again and the error bars expand. While these results were somewhat inconclusive, we determined that it was best to avoid above a 5% error. Results from silicone printed by our system can then be compared to the 2%, 5%, 10% and 20% error sample results to determine whether 3D printing silicone creates more consistent samples compared to hand-mixing.

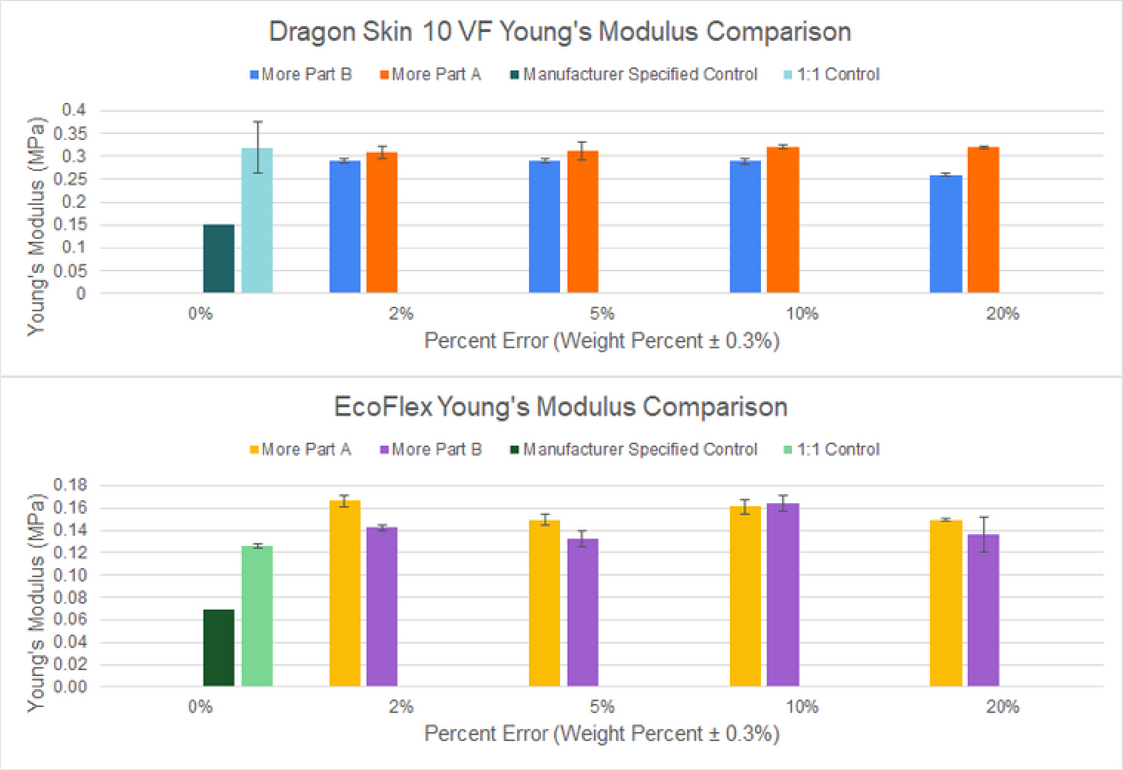


Figure 15: Results of Ecoflex and Dragon Skin tensile sample tests compared with a 1:1 control, and the Young's modulus specified by the manufacturer. Error bars represent the standard deviation calculated from a population of two samples.

Figure 16: Broken Dragon Skin 10 VF samples after tensile testing.

3.1.2 Accelerated Curing

Since we are using a two-part silicone that is chemically cured with cross linkers, heat added to the system will accelerate the cure time. The silicone can be heated through convection conduction, and radiation. To determine the effect each of these would have, we tested the effect these heating methods affected cure time and compared the effects on Dragon Skin and EcoFlex.

3.1.2.1 Heated Bed

The easiest implemented heating method is the heated bed as it is already implemented on the E3D. The maximum bed temperature of the E3D is 80 °C so we performed the tests at that temperature, with the philosophy of faster curing is better. Table1 below illustrates that the tests yielded positive results.

Curing Times		
Bed Temp (°C)	EcoFlex 00-35	DragonSkin 10 VF
20	7 Minutes	35 Minutes
80	13 Seconds	20 Seconds

Table 1: Time for EcoFlex and Dragon Skin to cure with and without a heated bed.

The cure time with a heated bed was a fraction of its original. This was very encouraging for the effectiveness of a silicone 3D printer, yet a quicker cure time would be ideal. In addition to conductive heating, the heated bed provides convective heating by heating the environment. This air heat would be of greater effect if the 3D printer was enclosed, but we decided the effects of an enclosure would not be worth the time and effort of installation for this project. We shared the E3D with other ongoing research, and did not want the enclosure to interfere. However, as the print increases in height, the conductive heat transfer decreases. Accelerated curing relies more and more on the less effective convective heating as the print progresses, therefore we determined that we needed an additional form of accelerating curing that does not rely on proximity to the print bed.

3.1.2.2 Infrared Lamps and Multilayer Curing

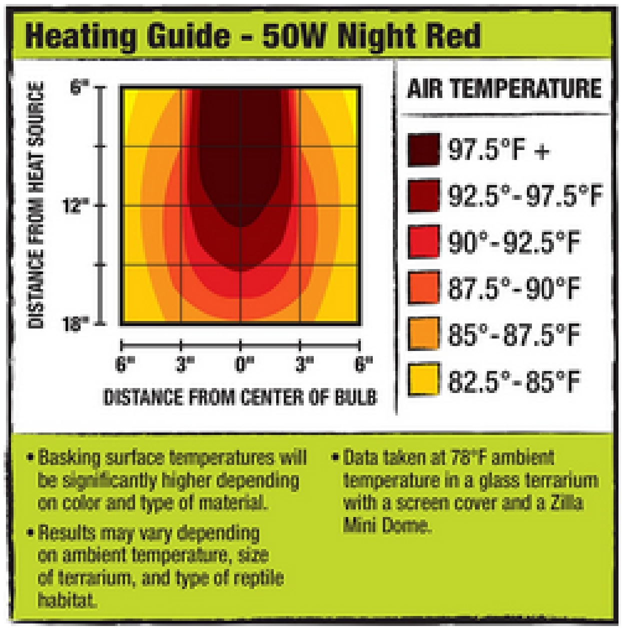
We decided to use heat lamps to assist with accelerated curing with radiant heat. Heating via infrared lights is crucial to the 3D printing process for prints as the distance from the print bed increases. The more layers a print needs, the further away the silicone will be from the heated bed, and will need to rely on heat from another source to improve reaction time. With our testing, Dragon Skin took about 35 minutes to fully cure after mixing when exposed to no external heat. Using one infrared bulb, the cure time for Dragon Skin was reduced to 2 minutes. Within six inches below the halogen bulb, the air temperature increased to 97.5 °F (Fig.17), however, when we tested the heat at 1 cm (which is more realistic to the printer setup) the reading from a metal temperature probe was 170 °C. Using two of these bulbs in combination with a heated print bed would cure fast enough to deposit layers on top of each other without collapsing.

Printing on top of existing silicone layers could impact the curing time of the higher layers due to heat from the bed being reduced by the distance between the bed and the silicone. To test the significance of this impact, a pool of silicone was placed on the print bed and once cured more silicone was placed on top and timed until it was completely cured. This test was conducted both with the print bed at room temperature (20 °C) and 80 °C as well as with two infrared lights about 1 cm above the silicone.

Ecoflex on Ecoflex Curing Times (s)		
Bed Temp (°C)	Lights On	Lights Off
20	420	23
80	11	5

Table 2: Time for a line of Ecoflex to cure on top of a layer of Ecoflex with and without heat sources.

As can be seen in Table 2, print bed temperature had the most significant impact on curing time, decreasing the curing duration from 420 seconds to 11 seconds. By applying heat from both the print bed and the infrared lights, the silicone cured in 5 seconds. This result supported our hypothesis that silicone would cure fast enough to be completed once the print process has concluded with negligible negative effects on curing time due to multiple layers.



- Basking surface temperatures will be significantly higher depending on color and type of material.
- Results may vary depending on ambient temperature, size of terrarium, and type of reptile habitat.
- Data taken at 78°F ambient temperature in a glass terrarium with a screen cover and a Zilla Mini Dome.

Figure 17: Graph of how Zilla Halogen bulb affects air temperature around heat source[14]

3.1.3 Material Comparison Conclusions

We had first tested with Dragon Skin 10 VERY FAST as Dragon Skin is a durable yet stretchable material commonly used in soft robotic research. However, for this project, the most important factor was cure time, so when Ecoflex 00-35 FAST was tested to be faster we chose it as our primary testing material. It may be possible to print Dragon Skin 10 VF with our system, but we did not have time to test both materials. With this change came a few benefits: Ecoflex is softer than Dragon Skin making it even more distinct from even the softest FDM-printable TPUs like NinjaTek Chinchilla 75A while being more affordable per kg[3]. Another benefit of Ecoflex 00-35 was the uncured viscosity of 3,500 cps as opposed to Dragon Skin 10 VF's 25,000 cps [4], [8]. This lower viscosity made the pump prime much easier and decreased the power required by the pumps. The two parts also mixed more easily in the mixing nozzle as they were pushed through.

3.2 Pump Selection

Choosing the right pump to extrude silicone was important because we needed to find an option that would meet our needs without exceeding our budget. In order to pump silicone, the pumps had to create a vacuum seal so they could self-prime by pulling silicone from the reservoirs through the system. The pumps needed to be able to move viscous materials, and have a fairly consistent flow rate. One objective of printing silicone was to minimize the number of air bubbles and other defects in the prints, so any pump that might introduce extra air into the system was deprioritized. According to our tolerance experiments, anywhere below a 5% error in weight ratio would no impact the material properties, and anywhere below 20% error would still fully cure. Therefore, while optimal, it was not necessary to have an extremely high-precision pump. This helped us select a pump that would work for our needs while staying within our budget. The pump options we explored are shown in Fig. 18.

3.2.1 Screw Pump

Screw pumps move material through a long cavity in the stator with a screw-shaped rotor (A in Fig. 18). The stator is made from a flexible material and deforms around the rotor to create a vacuum

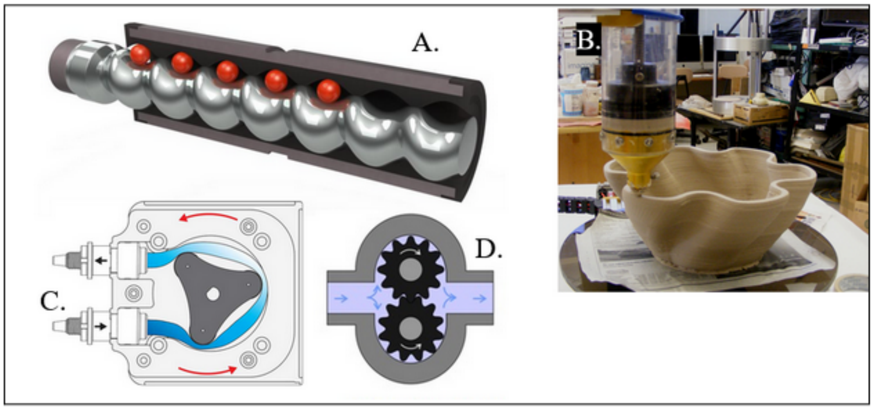


Figure 18: Pump options we investigated for extruding silicone.

seal [16]. This seal is important because it enables the pump to self-prime. One commercial solution to printing silicone is sold by Viscotech, which uses precise “Endless Piston” screw pumps to achieve a very consistent flow rate and constant volume extrusion[17]. These pumps were used successfully by another group investigating the material properties of printed silicone samples[15]. Large-scale screw pumps are the industry standard for moving highly viscous materials such as viscous food products (i.e. ketchup or peanut butter) or wastewater sludge. These pumps are high precision, and their specific geometry and construction drive up the cost. The cheapest version of this pump on the scale of our system that we could find was quoted at around $3,000, which exceeded the total budget for this project. The screw pump provided a high-precision solution excellent for viscous materials but was ultimately too expensive.

3.2.2 Syringe Pump

The syringe pump is one of the simplest ways to pump a viscous material. This method was successfully used by another group using silicone to print soft robotic actuators [28]. Syringe pumps are also used on 3D Potter printers, which extrude a mixture of clay and water that holds its shape and can be fired[9]. The 3D potter pump is shown in Fig. 18 B. While these pumps provide a very cheap and simple way to move viscous materials, they can’t be refilled while a print is in progress, and require the whole plunger to be removed in order to add more material. Another downside is the potential inclusion of air pockets when pressing the plunger into the silicone. One of our objectives with this system was to minimize the number of air bubbles in final prints because such defects usually initiate fractures. We decided not to use syringe pumps because we wanted to be able to refill the reservoirs easily and without making a mess. We were also concerned about forcing air into the system and unwittingly creating defects in the prints.

3.2.3 Gear Pump

We tested gear pumps (Fig. 18 D) as they are self-priming, bidirectional, and the lower-end industry standard for oils and other similar viscosity fluids. However, gear pumps have very small orifices, which are not optimal for high-viscosity fluids. We found $30 gear pumps and tested them with water and then silicone (Fig. 19). The pumps worked very well with water, self-priming and running smoothly. However, the pumps were iron and began to rust internally, we lubricated them in attempts to counteract this issue, but once there was rust in the pumps it was a losing battle. The pumps would jam and were slowly eating away at themselves. This pump was made to pump oil and be lubricated by the fluid it pushes, but the silicone we pushed did not act as a sufficient lubricant. This means a gear pump would have to be cleaned and re-lubricated periodically. In addition to the mess and time consumption this would cause, trace amounts of lubricant would be mixed into the silicone parts changing the print’s material properties. Thus, we avoided any pump system that would require lubrication or had a risk of rusting. The other key takeaway from the gear pumps was that it takes a great deal of negative pressure to pull silicone through a tube for self-priming.

We had to increase the size of the tubes on the input significantly to allow the high-viscosity silicone to flow with the negative pressure created by the gear pump.

Figure 19: Testing two gear pumps with Dragon Skin 10 VF

3.2.4 Peristaltic Pump

Peristaltic pumps (Fig.18 C) pump, in the same way, our intestines move the food and fluids we consume, squeezing a tube along a length, creating positive pressure in front of the push and a vacuum behind. Peristaltic pumps have significant advantages and disadvantages in comparison to the other pump types. The greatest assets of the peristaltic pump are its simple, and therefore cheap, construction and continuity, meaning the fluid never switches tubes or enters into something foreign making contamination impossible if the proper tubes are chosen. The primary disadvantage of peristaltic pumps is the innate inconsistency in flow rate and thus difficulty in determining the pump's flow rate at any given moment.

3.3 Peristaltic Pump Design

We determined the peristaltic pump to be our best pump type given our budget, time constraints, and needs. To overcome the viscosity of the silicone in suction (for self-priming), a large diameter tube was used (9mm OD and 6mm ID). This large tube has to be soft for the peristaltic pump to squeeze the tube and push the silicone peristaltically. To keep the tubes light and limit the amount of silicone wasted on a purge, smaller tubes (3mm ID) were used between the pump and the printhead. These tubes were harder than the large tube to prevent the pliability of the tube from acting as a spring in the pressure system. The pressure of the system is determined by the rate of the pump input, and the size of the smallest orifice (which is simply a small hole) we designed the system to have the smallest orifice at the very end of the print nozzle so that the flow never has to fill a lower pressure volume other than the end of the print nozzle.

Peristaltic pumps have two or more rollers. The more rollers in the pump, the more frequent the interruptions in flow, however, the pressure is more consistent. Most peristaltic pumps have three rollers to balance these two factors, we chose to have two rollers rather than three because having flow from both parts of the silicone is more important for our project than consistent pressure. The peristaltic path of the tube is 200°and the rollers are offset by 180°giving 20°of overlap in which the roller that is starting the peristaltic path can build up pressure. The first iteration (Fig. 20) attempted a rounded profile for the roller and peristaltic path in attempt to combat the tendency of the tube to form an incomplete flow stoppage on the fold points of the tube. This technique failed to seal properly and therefore couldn't pull a vacuum.

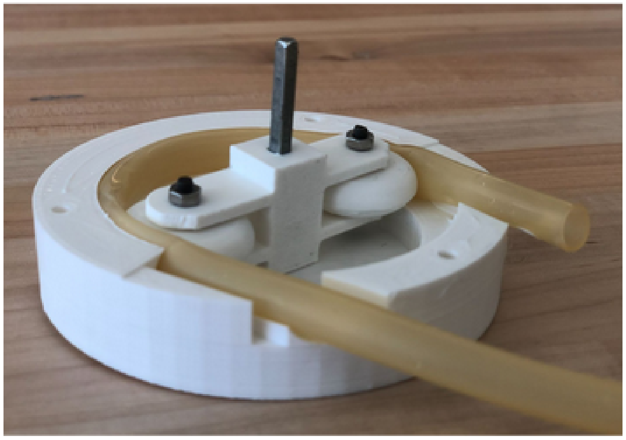


Figure 20: Inside an early peristaltic pump prototype.

There were at least seven design iterations after switching to flat rollers, including adding bearings, switching shaft types, changing tubes and pump radius. To overcome the change in pressure based on the rotor phase, we offset the pumps 90° from each other. This meant the flow was more consistent, but the ratio of parts A and B would change based on the combined phase of the two pumps.

3.4 Printhead System Design

The final system consisted of two glass aspirator bottles for storing silicone attached to flexible PVC tubes. These tubes ran through our 3D-printed peristaltic pumps and connected to smaller diameter, harder tubes on the other side. These small tubes carried the silicone down to an H-splitter connection that kept the two parts separate while funneling both into our static mixing nozzle. This nozzle extruded silicone onto the heated bed of the E3D. We attached heat lamps to the sides of the structure holding the mixing nozzle in order to accelerate curing. The peristaltic pumps were driven by one stepper motor (as outlined in Fig. 21), which was easy to control with the G-code provided by the slicer for the E3D system.

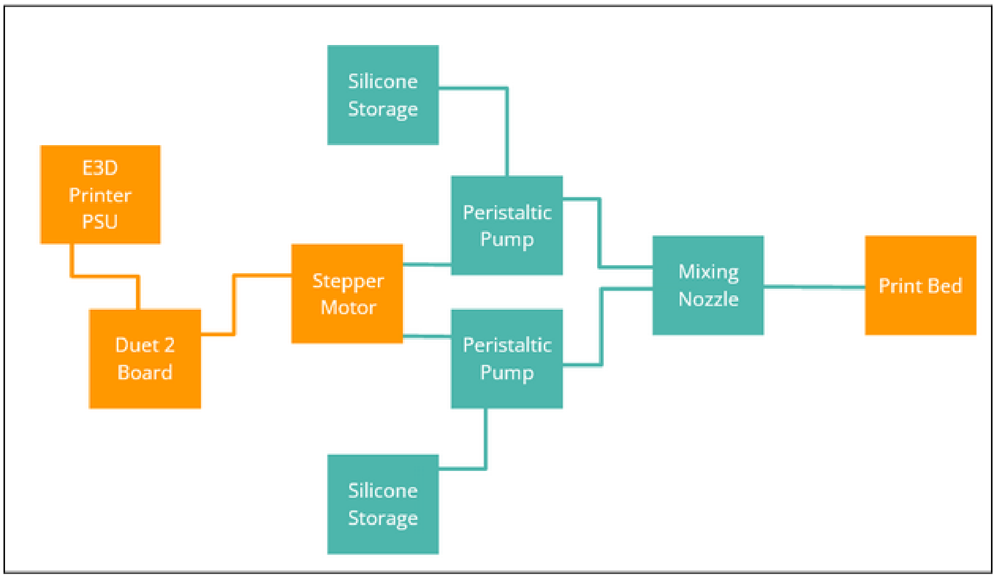


Figure 21: Diagram of the system with all components labeled. Teal components are purely mechanical, and orange components have an electrical component.

3.4.1 Tube Selection

Choosing the tubes to carry silicone from the aspirator bottles to the mixing nozzle was challenging because many common materials used for flexible tube construction will inhibit silicone curing. According to the manufacturer, latex and nitrile will contaminate the silicone and prevent curing. Tin-cured silicone can inhibit the curing of platinum-cured silicone, therefore we decided against silicone tubes as we could not verify that they would not contaminate our mixture [19]. Because we needed a larger diameter, flexible tube to run from the silicone container through the peristaltic pumps, we decided to use soft PVC with an inner diameter of 6mm and a shore hardness of 30A. For the smaller tubes running from the pumps to the mixing nozzle, we chose harder vinyl tubes with an inner diameter of 3mm and a shore hardness of about 80A.

3.4.2 Mixing Nozzles

In order to mix the two-part silicone, we used disposable static mixing nozzles commonly used for two-part epoxies, shown in Fig. 22 We chose these nozzles because they are extremely cheap, and provide a simple, static solution to mixing the parts A and B without requiring another motor or other mechanism. These nozzles are very common in the industry for epoxies with a similar viscosity to Ecoflex 00-35 FAST, therefore we were able to integrate them into the system and they immediately worked. The only downside to these mixing nozzles is that they are single-use and need to be swapped out after each print.

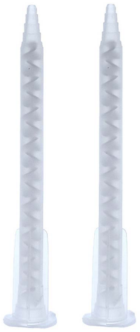


Figure 22: Disposable static mixing nozzles

3.4.3 H-Splitter

To integrate the mixing nozzle with tubes, an “H-splitter” was designed so both tubes would dispense simultaneously into the mixing nozzle. The splitter ensures that neither part A nor B interact with each other until they have reached the nozzle where they can be mixed properly. Unlike a Y-splitter, our splitter is designed for both parts to stay completely separate until they leave the splitter and enter the nozzle, allowing the H-splitter to be reused for multiple prints since silicone will only cure once inside the mixing nozzle. This design is shown in Fig.23.

3.4.4 Heating System

In order to accelerate curing, especially on taller layers that are not in contact with the heated bed, we added heat lamps to the sides of the printhead. We did not integrate control of the lights into our software, and for this project we plugged them in near the printer and turned them on manually at the start of the print.

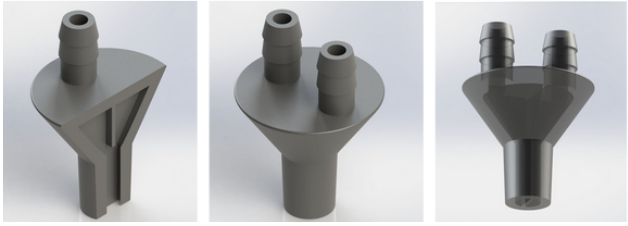


Figure 23: Renders of the H-splitter and its cross-section

Figure 24: Printhead with heat lamps attached

3.4.4.1 Thermal Protection

As the heat lamps reached temperatures of over 170 °C, we needed to prevent melting plastic parts or damaging cables. During testing these bulbs melted PLA components after 3 minutes at 15 millimeters between the bulb and PLA. We added an aluminum sleeve to the outside of the printhead, as shown in Fig. 24, and wrapped it with thermally reflective tape commonly used for ducts. This tape had a fiber backing which helped insulate the tube from radiant heat. The aluminum sleeve both prevented the PLA printhead from being damaged and helped extend the pot life of silicone in the mixing nozzle to prevent clogging. We also wrapped reflective tape around the bulb cables to prevent melting. As the bulbs are usually installed in a reflective light fixture, the cables were not made to withstand extreme temperatures. These precautions were effective, as the plastic printhead did not sustain any thermal damage during printing.

3.4.5 Gearbox Design

As anywhere within a 5% error in the mixed ratio of parts A and B was determined to be acceptable, we ran both pumps off of one stepper motor as shown in Fig. 25. We assumed the difference in pump output would not be greater than 5%, and with the pumps out of phase with each other our flow rate was consistent enough that we did not need to drive them independently. We used bevel gears to drive both pumps from our stepper motor, and added a flex coupler to prevent strain on the gearbox from shaft misalignment.

In order to preserve our stepper motor, we determined it should run at about 80 rpm for maximum efficiency. Estimating that the extruder will move in X and Y at about 45 mm/minute ($v_{extruder}$) extruding a 1mm by 0.5mm line on the print bead, we calculated the volumetric flow rate Q. We then calculated the output volume per rotation from our peristaltic pumps, and used that to determine the output speed of our gearbox. We used these numbers to calculate the necessary gear ratio to run the pumps at the right speed without stalling or damaging our stepper motor.

$$Q = v_{extruder} * line_{width} * line_{height} = 22.5 \frac{mm^3}{s} \tag{1}$$

$$\omega_{out} = \frac{Q}{V_{out}} = 0.394 rpm \tag{2}$$

$$ratio = \frac{\omega_{in}}{\omega_{out}} = 203.1 \tag{3}$$

We achieved the 200:1 gear ratio by purchasing an off-the-shelf 100:1 planetary gearbox, and attaching it to our brass bevel gears with a ratio of 2:1.

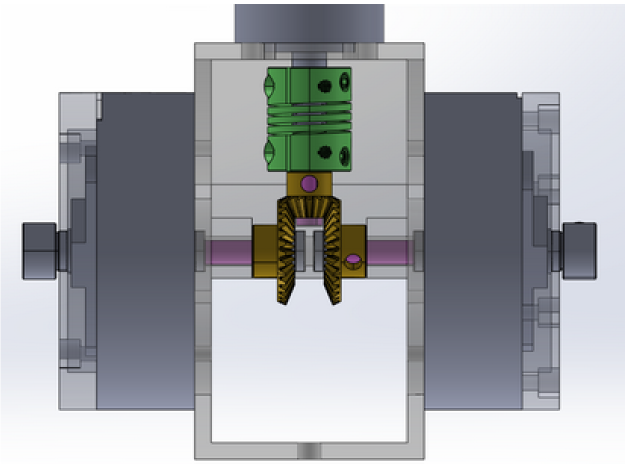


Figure 25: Solidworks model of the splitter gearbox design

3.4.6 E3D Interface

As our printhead needed to integrate with an existing system, the design of the E3D shaped our prototyping process. A major benefit of choosing to use pumps over syringes was the ability to control the system using a single stepper motor. Most E3D printheads use one stepper motor, this made our design seamlessly compatible with the existing software (SuperSlicer) and setup of the ToolChanger. Thus, the G-code generated by any Superslicer was compatible with our silicone printing system with minimal adjustments. As with any new printhead, we needed to specify a few print parameters, but we did not need to use any additional software. As with any new E3D tool, there were initial calibrations required to align the printhead with the dock, adjust the appropriate bed height, and avoid colliding with the lead screw when putting the printhead back.

4 System Testing and Validation

To test system functionality, we first checked for leaks by pressurizing the tubes with compressed air. We then ”printed” by manually running the stepper motor with an extra Duet 2, power supply, and a laptop, to determine if the pumps were extruding equal amounts of silicone and to ensure our prints cured fast enough to create multiple layers. After validating the basic mechanical functionality, we attached the system to the E3D and tuned the print parameters. We then printed a tensile sample to compare with our data from cast samples. The full printer setup is shown in Fig. 26

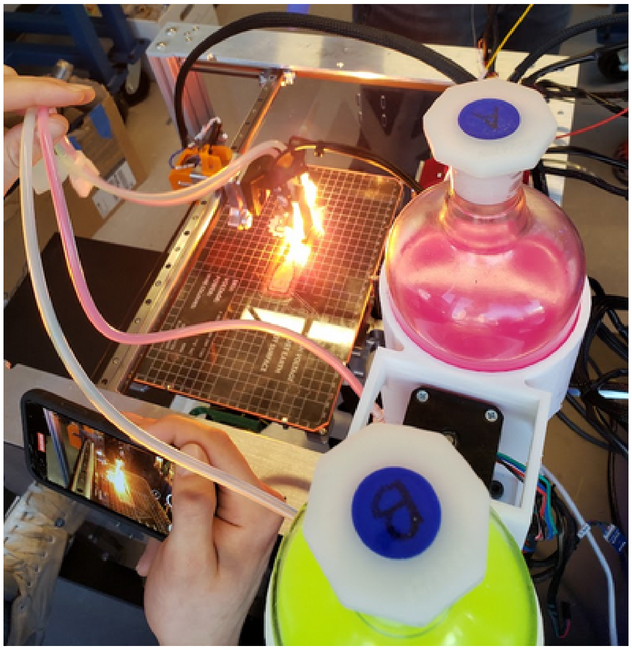


Figure 26: Printing a dogbone sample on the E3D

4.1 Leak Testing

Before putting silicone in the system, we pressurized the tubes with compressed air to validate that none of the fittings would pop off, causing a spill. While Ecoflex is at worst a mild skin irritant if touched [8], uncured silicone must be removed with isopropyl alcohol and can be a messy and difficult cleanup. As we were sharing the E3D with other ongoing 3D printing research, it was important to make sure our system did not spill on the ToolChanger. When we pressurized the system, the gauge we were using to measure pressure disconnected at 0.3 MPa, while all our system components held. With the gauge disconnected, we increased pressure by blocking off the end of the mixing nozzle to determine where our system would fail first. Air leaked from the connection between the H-splitter and the mixing nozzle, as the splitter connector was press fitted into the end of the mixing nozzle. We decided this weak point did not need to be fixed because we did not anticipate pressure buildup in the mixing nozzle (causing the joint to leak) in operating conditions.

4.2 Manual Extrusion

Before attaching the printhead to the E3D, we tested the system manually by plugging a spare Duet 2 board into a laptop and sending commands to the stepper motor via Pronterface. We used the heated bed on a spare FDM printer to extrude and cure silicone, simulating the ToolChanger environment. Using Pronterface, it was easy to increase the extrusion rate and quickly prime the whole system.

To test if our pumps were printing evenly, we detached the printhead from the tubing and put each tube in a separate cup. After running the pumps for about a minute, we removed the tubes and weighed the two parts of silicone. There was a 10% difference in the weights of parts A and B, which suggested that while the prints would still cure, the material properties may differ from a 1:1 ratio. This disparity was most likely caused by slippage in the set screw connection from the drive shaft to the pump rotors but may have also been affected by slight differences in 3D-printed pump geometry.

We dyed parts A and B different colors to be able to visually judge the consistency of extrusion from both pumps. With a high feed rate, we extruded a long puddle onto a clean surface to compare the resulting colors as shown in Fig.27 The variation in colors shows the output from our two peristaltic pumps aligned out of phase with each other. The difference in the ratio of part A to B may cause a slight difference in material properties throughout a single part, but with many small extruded lines this discrepancy might be negligible. Further testing is required to determine the effects, however, we decided to move forward as all of our test prints cured fully.

Figure 27: Duty cycle of each peristaltic pump shown with dye

After successfully extruding lines by hand, we tested stacking layers manually on a heated bed. With the bed at 80 °C and both heat lamps on, we were able to produce layers of silicone successfully without creating a puddle. One of these test prints is shown below in Fig.28

Additionally, a manual print of a dogbone structure and a print with one shell walls was conducted to see how well the silicone cured together when printing on top of one width and how silicone would cure if its distance increased from the heated print bed. The results of these prints can be found in Fig.29. We

Figure 28: Layers of silicone printed by hand without pooling

found that as we increased the speed of the stepper, the mix was more even over time, this influenced our print speed on the E3D ToolChanger.

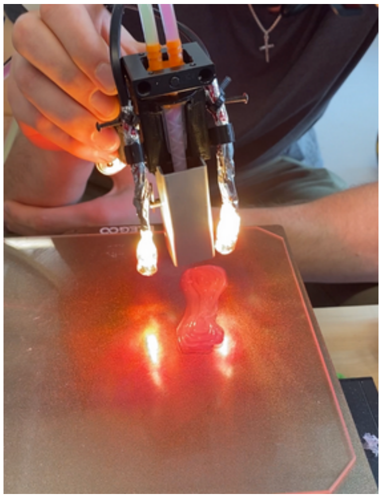


Figure 29: Multi-layer hand print result

4.3 Printing on the E3D

The integration onto the E3D was physically very quick, only requiring two bolts (which were unfortunately somewhat tedious to access), plugging the stepper motor into the board, and plugging in the two IR Lights into an outlet. We then calibrated the printhead pickup, drop off, and proper bed height. This concluded the set up, we then sliced some test samples using SuperSlicer[13] as shown in Fig.30

In the slicer software, we created a new toolhead and filament so we could save our custom print setting. The nozzle is 1.27mm wide, so we set the line width to 1.5mm as making line widths slightly greater than the nozzle width is optimal. Layer height was set to 0.5mm since a layer height between one-third and one-half of nozzle width produces the best results. The hotend temperature was set to 0 °C as there is no heating element controlled by the Duet board. We set the speed to 35mm/s across the board as it produced the cleanest results. The Extrusion multiplier was set to 0.8 to get the appropriate amount of silicone to extrude per cross-sectional area. A skirt was added to all parts so that the fresh mixing nozzle would be filled with part A and B before the actual part began. More print settings are detailed in Appendix C. The resulting printed dogbone is shown in Fig. 31.

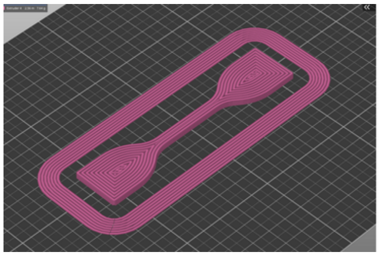


Figure 30: Dogbone sample model after being sliced with custom settings for silicone

Figure 31: Dogbone sample printed on the E3D

4.4 Print Quality

We examined the quality of our printed silicone by printing tensile specimens and comparing them to cast specimens. For this experiment, we tested samples cast from pump output before the mixing nozzle, cast from mixing nozzle output, and printed on the E3D. Ideally, this would inform us how printing the silicone affected the material properties, however our specimens were limited by access to the printer. Unfortunately, we were only able to collect data from one printed sample, as the rest were printed before we finalized the print settings and contained significant structural defects. A comparison of Young's modulus (Fig. 32) showed that the hand-mixed cast sample had the lowest value. The Young's modulus specified by Smooth-On is 0.069 MPa. We were also interested in the dimensional accuracy of the silicone prints. We measured the outside XY perimeter to be 1.3 mm greater than the CAD which makes sense since the diameter of the nozzle is 1.27 mm and the way the part was sliced, the nozzle follows the outside perimeter of the STL, adding its radius to both sides of the print. The height was off by .4 mm which is 11% considering the part was only supposed to be 3 mm height. This is not a limitation of the system, but of our limited iteration of refining print settings. We were only able to print three parts before the end of the term which did not allow us to refine the flow rate. Based on the measurement results above, the flow rate should be dropped by approximately 10%. By adjusting these settings, it may be possible to create very precise and repeatable parts, in contrast to our cast samples which varied by up to a millimeter in height.

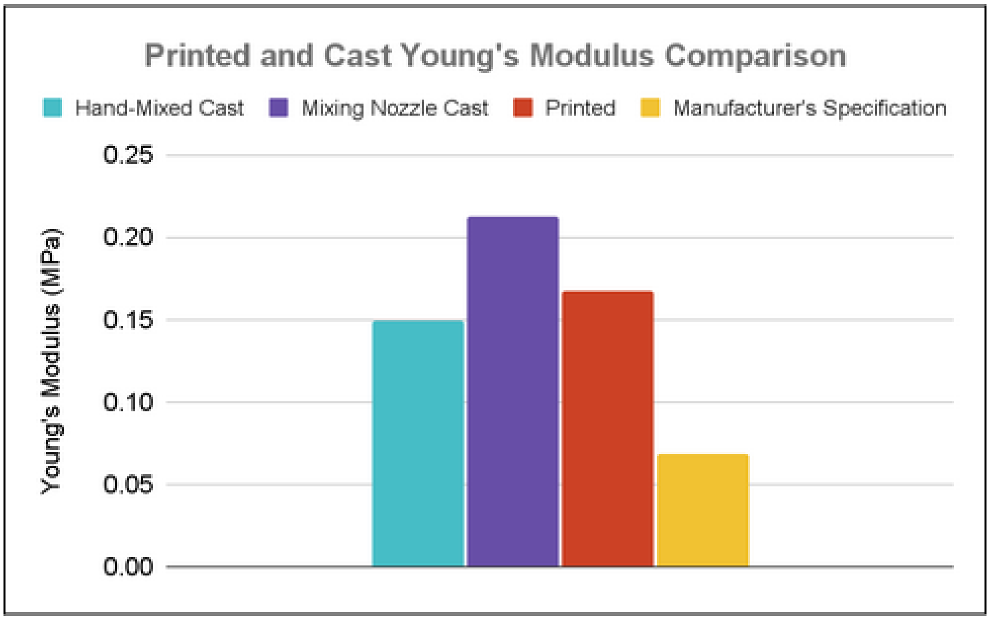


Figure 32: Young's modulus comparison of cast and printed samples

5 Discussion

The objective of this project was to design and fabricate a low-cost, modular print head to extrude silicone using the E3D ToolChanger system for soft robotics applications. This printer was requested as traditional FDM printing can only print soft materials down to a shore hardness of 50A. We successfully printed parts with Ecoflex 00-35 FAST, which has a shore hardness of 00 35 (the shore 00 scale is softer than shore A). Our system enables FDM printing of such a soft material, filling a niche need within the growing soft robotics field. While commonly used for constructing soft actuators, silicone is notoriously difficult to work with to produce consistent, repeatable parts [28]. Competing industrial silicone printing systems cost anywhere from $12,000 to over $25,000 [17], [24]. Our completed system cost under $250 to produce, making it accessible for soft robotics labs, hobbyists, or startup companies.

One of the biggest challenges with printing a two-part silicone mixture was ensuring that both parts were extruded equally. Since we were striving to cut costs as much as possible, we anticipated some inconsistency in pump output. To determine the effect this might have on material properties, we tested the material properties of cast silicone samples with varying percent errors in the weight ratio. While these tests were limited by a small sample size, we concluded that material properties begin to fluctuate after a 5% error in the weight ratio. When we tested our completed system, we found a 10% error in the weight ratio of the extruded parts. This likely had an effect on our printed samples, however, further investigation is required to determine exactly how the properties differ from a 1:1 ratio, as our tests were conducted with a very limited sample size.

One important requirement for printing silicone for soft robotics is being able to cure layers quickly enough to print tall structures. We accomplished this accelerated curing by printing on a heated bed with two heat lamps mounted on the printhead. With these additions, we lowered the Ecoflex cure time from five minutes to five seconds, making it possible to stack layers without the print collapsing into a puddle. This curing strategy proved effective for creating dimensionally accurate prints, however, we did not investigate the effect of accelerated curing on the material properties of the silicone print.

By only designing and developing the printhead, it was crucial for this design to be compatible with the E3D ToolChanger. The interface that runs the ToolChanger allows for G-code to be implemented that is generated by a slicer, such as SuperSlicer which was used for this project. This G-code controls how the printheads move in X and Y, when the stepper motor needs to move for extrusion, and retraction of material if necessary. Our design successfully completed our goal of being 100% compatible with the existing E3D operating practices. Our team was able to put our print design in SuperSlicer, compile the necessary G-code for the print, and upload it to the E3D to complete silicone printing. This process makes it possible for anyone using the E3D to implement our system without the need to learn any new programs. This ease of use could even extend to other multi-material printers that allow for the addition of custom printheads.

6 Conclusions and Recommendations

6.1 Conclusions

This project filled a niche need for the growing soft robotics field, which required soft parts that could be repeatedly manufactured with more precision than hand-mixing and casting could produce. Traditional FDM printing had a lower limit on the softness of filament, which was higher than the needs of soft robotics. By developing a modular print head to attach to an existing tool changer system, we provided a more accessible solution than any existing products on the market because it was several orders of magnitude cheaper. The system integrated with the existing E3D ToolChanger hardware and slicer, without requiring any additional software modifications. While there was some inconsistency in output from the pumps, this issue could be mitigated by using machined pumps instead of our 3D-printed prototypes, which were prone to slippage. Despite the error in the output, our prints were able to cure fully and perform tensile tests. We successfully accelerated the curing process by printing on a heated bed and adding heat lamps to the printhead. This extra heat dramatically shortened the cure time of our silicone, enabling multi-layer printing without dimensional inaccuracies caused by tacky silicone.

While our printhead can successfully print soft materials which are very useful for soft robotics, it is important to consider the ecological impact of 3D printing non-biodegradable materials. Silicone being non-biodegradable is a desirable trait for applications that require bio-compatibility, such as medical robots, however generating lots of silicone scraps and prototypes will have an impact on the environment. In addition to silicone, our printer depends on single-use plastic mixing nozzles, which must be thrown away after each use. One potential improvement on this system would be to develop a mixing nozzle solution that can be easily cleaned between prints and does not need to be thrown out and replaced.

Our WPI undergraduate education prepared our team well for this MQP by providing us with the necessary technical knowledge and problem-solving skills. Our experience working on this project gave us a better understanding of the design and fabrication process and provided us with practical experience in addressing real-world problems. This project allowed us to apply what we learned in the classroom to a real-world project, preparing us for our future careers in engineering.

6.2 Recommendations

For future teams and individuals working on this project we have compiled a few suggestions for improvements to the system. The first suggestion is to make the rotor of the peristaltic pump out of a studier material, ideally metal, to ensure that the rotor does not strip on the shaft. This issue could also be improved by making the set-screws easier to tighten. To combat the change in concentration of part B over time, the pumps could be put back in phase with each other and the speed of the pump changed based on the position of the rotor (speeding up during the transition between rollers). This would allow for consistent flow while also keeping the ratio close to 1:1. Another useful addition would be a shield around the lights so that the print can be looked at without being blinded. This shield could be a shaded piece of glass or a fully opaque cover. To better decrease the cure time of the silicone outside the nozzle, and increase the cure time inside the nozzle, semiconductor refrigeration tablets could be attached to the aluminum tube. These tablets cool one side and heat the other, this could be used to actively cool the aluminum tube (and therefore the nozzle) while increasing the temperature outside the tube thus increasing the ambient temperature and accelerating the cure time. It would also be interesting to determine the effect of the heat-accelerated curing on the material properties of silicone so that the nozzle effect can be separated from the quick cure effect.

We also had a list of tests that we believe would test the capabilities of this print head. This included printing multiple tensile samples in one print, an XYZ calibration cube, a conical height test, a single-layer spiralized cylinder height test, a four-channel air seal test, and a multi-material actuator.

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Appendices

A Tensile Testing Results

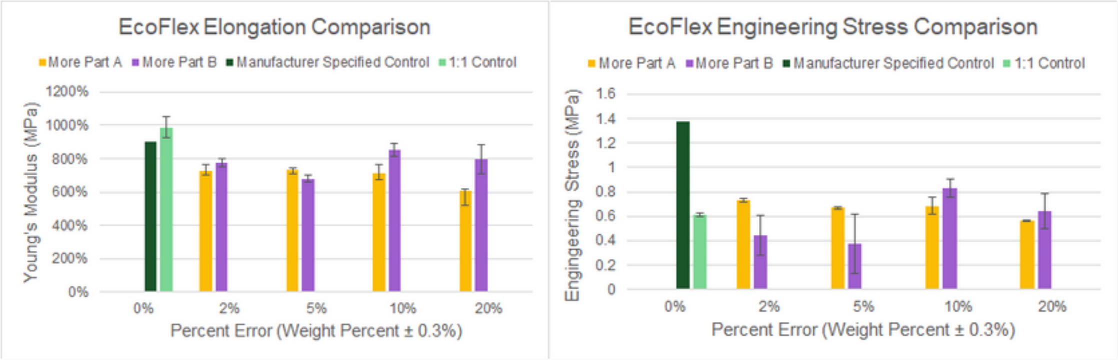


Figure 33: Ecoflex 00-35 tensile testing performance

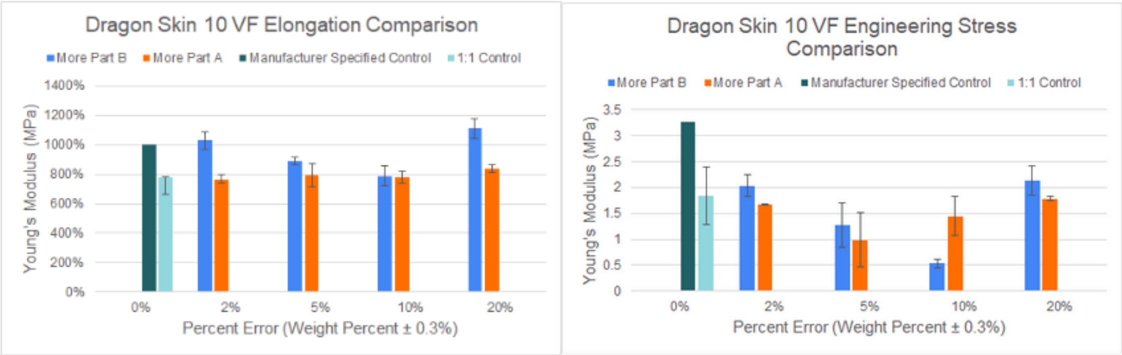


Figure 34: Dragon Skin 10 VF tensile testing performance

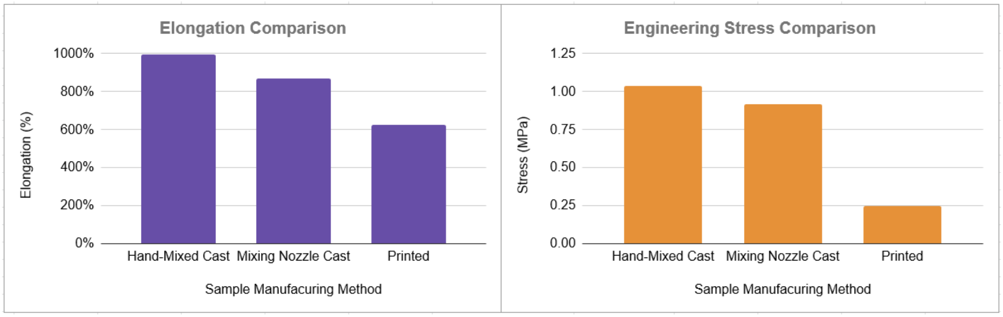
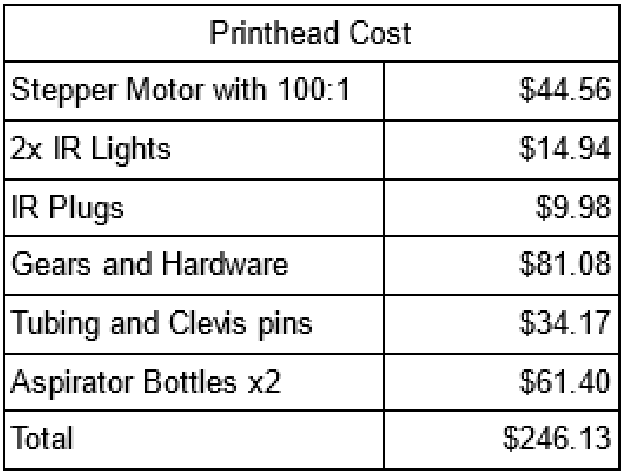


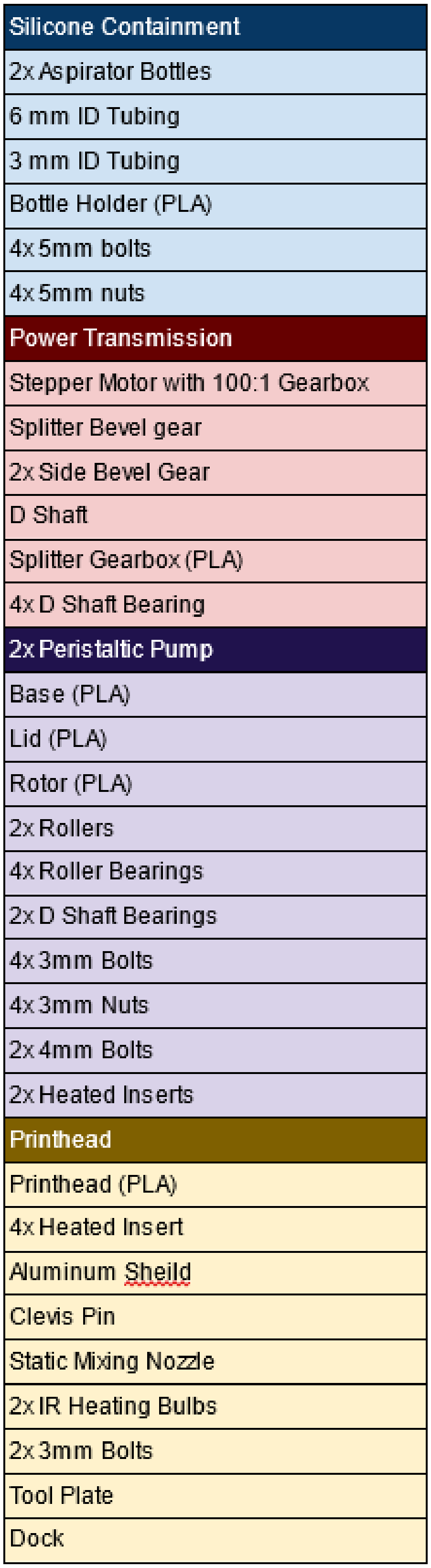
Figure 35: Ecoflex 00-35 printed vs cast sample tensile testing performance

B Bill of Materials

CAD models and documentation can be found on our GitHub.

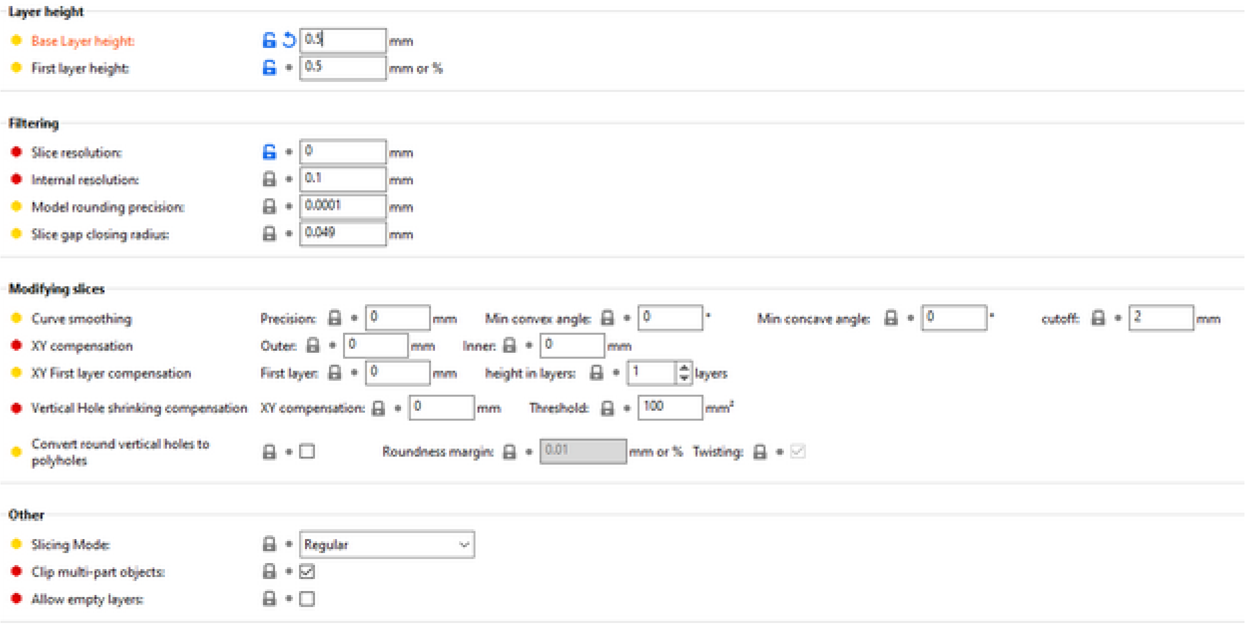


Printhead Cost	
Stepper Motor with 100:1	$44.56
2x IR Lights	$14.94
IR Plugs	$9.98
Gears and Hardware	$81.08
Tubing and Clevis pins	$34.17
Aspirator Bottles x2	$61.40
Total	$246.13



Silicone Containment
2x Aspirator Bottles
6 mm ID Tubing
3 mm ID Tubing
Bottle Holder (PLA)
4x 5mm bolts
4x 5mm nuts
Power Transmission
Stepper Motor with 100:1 Gearbox
Splitter Bevel gear
2x Side Bevel Gear
D Shaft
Splitter Gearbox (PLA)
4x D Shaft Bearing
2x Peristaltic Pump
Base (PLA)
Lid (PLA)
Rotor (PLA)
2x Rollers
4x Roller Bearings
2x D Shaft Bearings
4x 3mm Bolts
4x 3mm Nuts
2x 4mm Bolts
2x Heated Inserts
Printhead
Printhead (PLA)
4x Heated Insert
Aluminum Sheild
Clevis Pin
Static Mixing Nozzle
2x IR Heating Bulbs
2x 3mm Bolts
Tool Plate
Dock

C SuperSlicer Settings



Layer height

Base Layer height: 0.5 mm
First layer height: 0.5 mm or %

Filtering

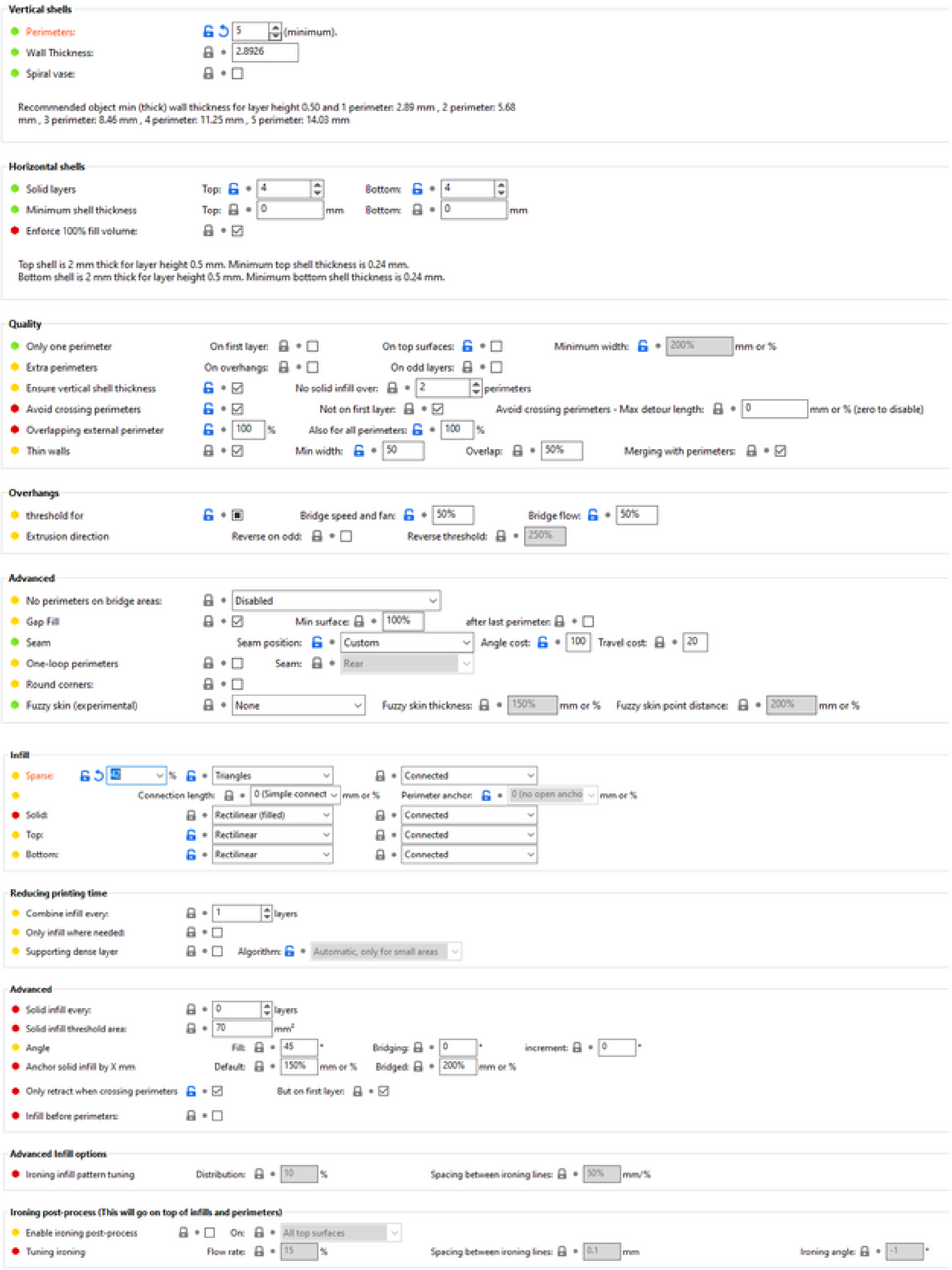
Slice resolution: 0 mm
Internal resolution: 0.1 mm
Model rounding precision: 0.0001 mm
Slice gap closing radius: 0.049 mm

Modifying slices

Curve smoothing — Precision: 0 mm — Min convex angle: 0 ° — Min concave angle: 0 ° — cutoff: 2 mm
XY compensation — Outer: 0 mm — Inner: 0 mm
XY First layer compensation — First layer: 0 mm — height in layers: 1 layers
Vertical Hole shrinking compensation — XY compensation: 0 mm — Threshold: 100 mm²
Convert round vertical holes to polyholes: ☐ — Roundness margin: 0.01 mm or % — Twisting: ☑

Other

Slicing Mode: Regular
Clip multi-part objects: ☑
Allow empty layers: ☐



Vertical shells

- Perimeters: 5 (minimum).
- Wall Thickness: 2.8926
- Spiral vase: ☐

Recommended object min (thick) wall thickness for layer height 0.50 and 1 perimeter: 2.89 mm , 2 perimeter: 5.68 mm , 3 perimeter: 8.46 mm , 4 perimeter: 11.25 mm , 5 perimeter: 14.03 mm

Horizontal shells

- Solid layers — Top: 4 — Bottom: 4
- Minimum shell thickness — Top: 0 mm — Bottom: 0 mm
- Enforce 100% fill volume: ☑

Top shell is 2 mm thick for layer height 0.5 mm. Minimum top shell thickness is 0.24 mm.
Bottom shell is 2 mm thick for layer height 0.5 mm. Minimum bottom shell thickness is 0.24 mm.

Quality

- Only one perimeter — On first layer: ☐ — On top surfaces: ☐ — Minimum width: 200% mm or %
- Extra perimeters — On overhangs: ☐ — On odd layers: ☐
- Ensure vertical shell thickness ☑ — No solid infill over: 2 perimeters
- Avoid crossing perimeters ☑ — Not on first layer: ☑ — Avoid crossing perimeters - Max detour length: 0 mm or % (zero to disable)
- Overlapping external perimeter 100 % — Also for all perimeters: 100 %
- Thin walls ☑ — Min width: 50 — Overlap: 50% — Merging with perimeters: ☑

Overhangs

- threshold for ▣ — Bridge speed and fan: 50% — Bridge flow: 50%
- Extrusion direction — Reverse on odd: ☐ — Reverse threshold: 250%

Advanced

- No perimeters on bridge areas: Disabled
- Gap Fill ☑ — Min surface: 100% — after last perimeter: ☐
- Seam — Seam position: Custom — Angle cost: 100 — Travel cost: 20
- One-loop perimeters ☐ — Seam: Rear
- Round corners: ☐
- Fuzzy skin (experimental) None — Fuzzy skin thickness: 150% mm or % — Fuzzy skin point distance: 200% mm or %

Infill

- Sparse: [illegible] % — Triangles — Connected
- Connection length: 0 (Simple connect mm or % — Perimeter anchor: 0 (no open ancho mm or %
- Solid: Rectilinear (filled) — Connected
- Top: Rectilinear — Connected
- Bottom: Rectilinear — Connected

Reducing printing time

- Combine infill every: 1 layers
- Only infill where needed: ☐
- Supporting dense layer ☐ — Algorithm: Automatic, only for small areas

Advanced

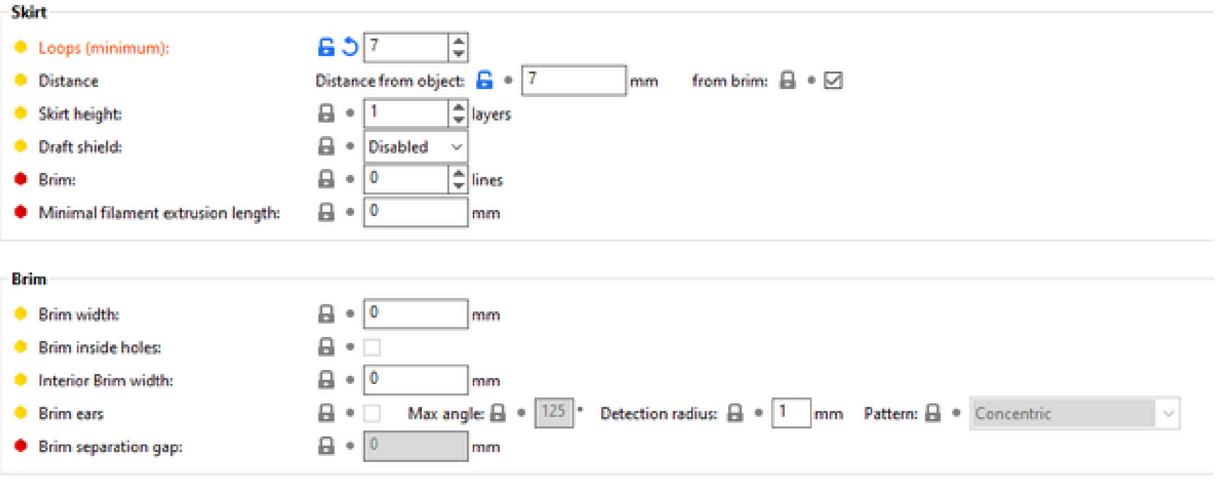
- Solid infill every: 0 layers
- Solid infill threshold area: 70 mm²
- Angle — Fill: 45° — Bridging: 0° — increment: 0°
- Anchor solid infill by X mm — Default: 150% mm or % — Bridged: 200% mm or %
- Only retract when crossing perimeters ☑ — But on first layer: ☑
- Infill before perimeters: ☐

Advanced Infill options

- Ironing infill pattern tuning — Distribution: 10 % — Spacing between ironing lines: 50% mm/%

Ironing post-process (This will go on top of infills and perimeters)

- Enable ironing post-process ☐ — On: All top surfaces
- Tuning ironing — Flow rate: 15 % — Spacing between ironing lines: 0.1 mm — Ironing angle: -1°

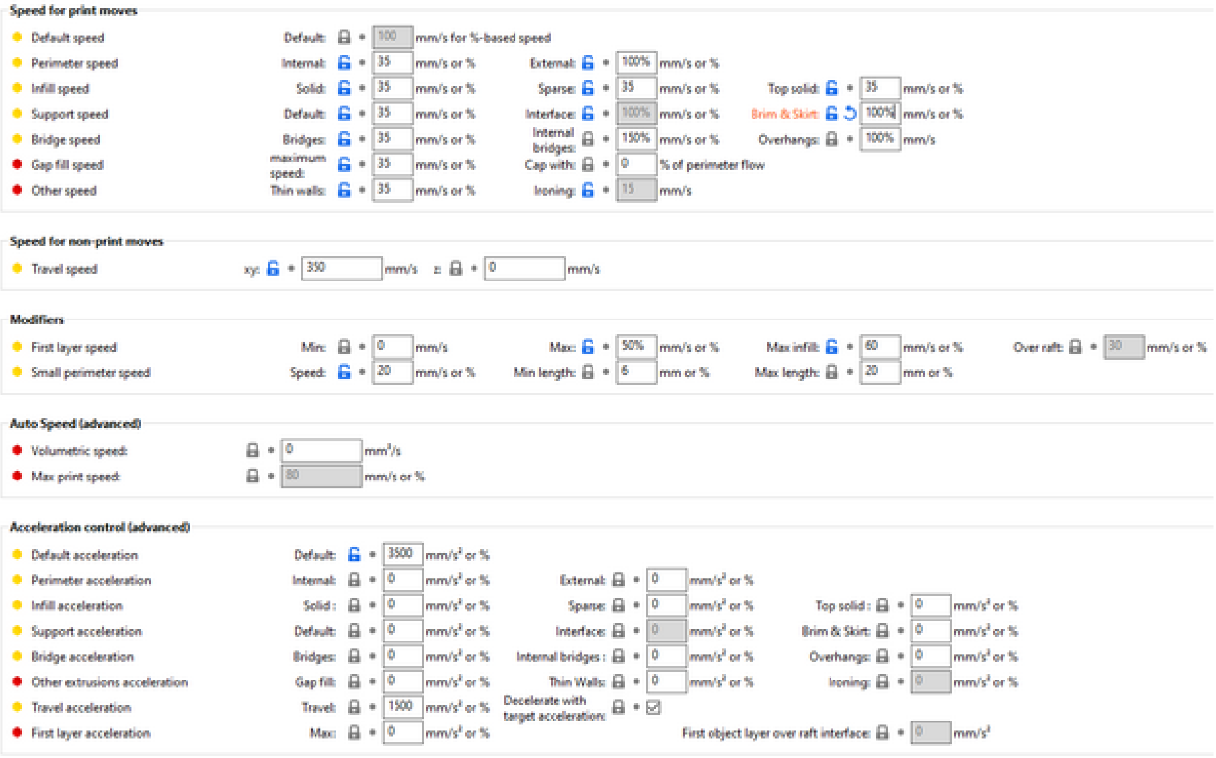


Skirt

- Loops (minimum): 7
- Distance: Distance from object: 7 mm; from brim: ☑
- Skirt height: 1 layers
- Draft shield: Disabled
- Brim: 0 lines
- Minimal filament extrusion length: 0 mm

Brim

- Brim width: 0 mm
- Brim inside holes: ☐
- Interior Brim width: 0 mm
- Brim ears: ☐ Max angle: 125 ° Detection radius: 1 mm Pattern: Concentric
- Brim separation gap: 0 mm



Speed for print moves

- Default speed: Default: 100 mm/s for %-based speed
- Perimeter speed: Internal: 35 mm/s or %; External: 100% mm/s or %
- Infill speed: Solid: 35 mm/s or %; Sparse: 35 mm/s or %; Top solid: 35 mm/s or %
- Support speed: Default: 35 mm/s or %; Interface: 100% mm/s or %; Brim & Skirt: 100% mm/s or %
- Bridge speed: Bridges: 35 mm/s or %; Internal bridges: 150% mm/s or %; Overhangs: 100% mm/s
- Gap fill speed: maximum speed: 35 mm/s or %; Cap with: 0 % of perimeter flow
- Other speed: Thin walls: 35 mm/s or %; Ironing: 15 mm/s

Speed for non-print moves

- Travel speed: xy: 350 mm/s; z: 0 mm/s

Modifiers

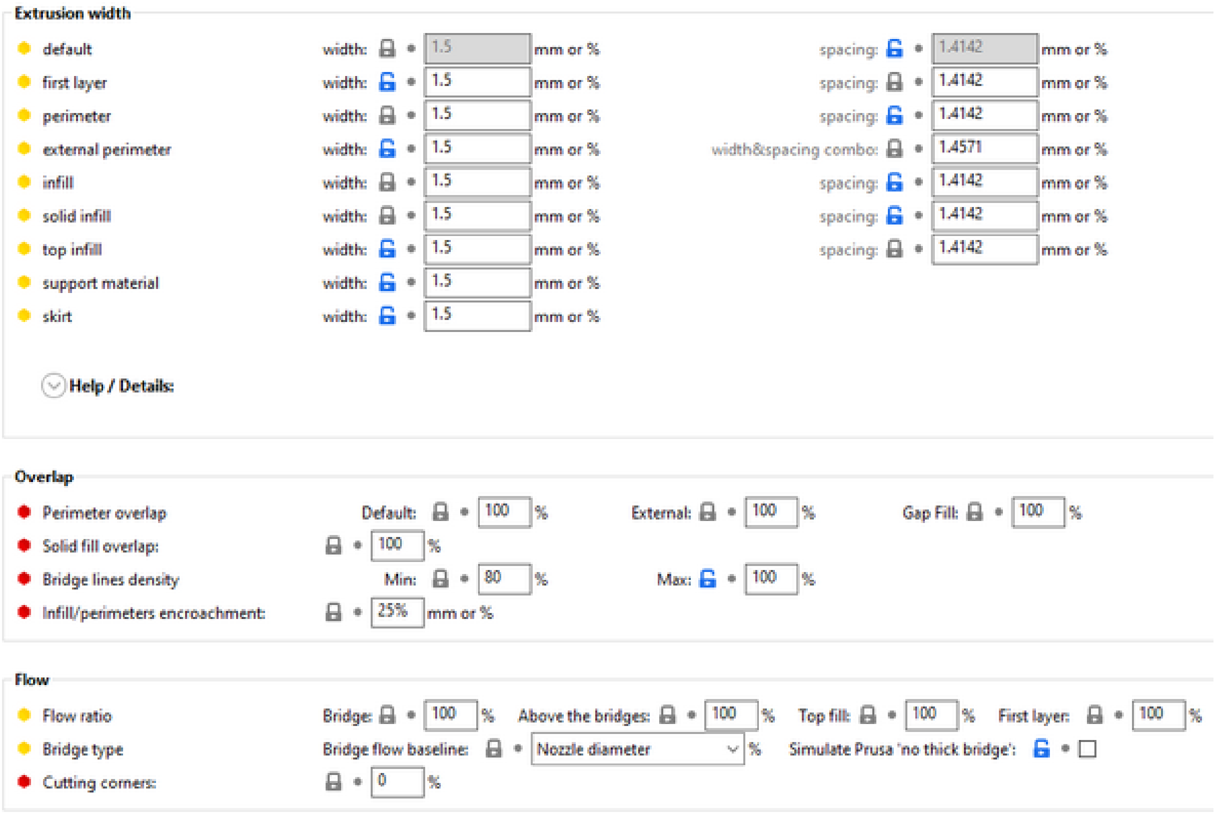
- First layer speed: Min: 0 mm/s; Max: 50% mm/s or %; Max infill: 60 mm/s or %; Over raft: 30 mm/s or %
- Small perimeter speed: Speed: 20 mm/s or %; Min length: 6 mm or %; Max length: 20 mm or %

Auto Speed (advanced)

- Volumetric speed: 0 mm³/s
- Max print speed: 80 mm/s or %

Acceleration control (advanced)

- Default acceleration: Default: 3500 mm/s² or %
- Perimeter acceleration: Internal: 0 mm/s² or %; External: 0 mm/s² or %
- Infill acceleration: Solid : 0 mm/s² or %; Sparse: 0 mm/s² or %; Top solid : 0 mm/s² or %
- Support acceleration: Default: 0 mm/s² or %; Interface: 0 mm/s² or %; Brim & Skirt: 0 mm/s² or %
- Bridge acceleration: Bridges: 0 mm/s² or %; Internal bridges : 0 mm/s² or %; Overhangs: 0 mm/s² or %
- Other extrusions acceleration: Gap fill: 0 mm/s² or %; Thin Walls: 0 mm/s² or %; Ironing: 0 mm/s² or %
- Travel acceleration: Travel: 1500 mm/s² or %; Decelerate with target acceleration: ☑
- First layer acceleration: Max: 0 mm/s² or %; First object layer over raft interface: 0 mm/s²



Extrusion width

default	width: 1.5	mm or %	spacing: 1.4142	mm or %
first layer	width: 1.5	mm or %	spacing: 1.4142	mm or %
perimeter	width: 1.5	mm or %	spacing: 1.4142	mm or %
external perimeter	width: 1.5	mm or %	width&spacing combo: 1.4571	mm or %
infill	width: 1.5	mm or %	spacing: 1.4142	mm or %
solid infill	width: 1.5	mm or %	spacing: 1.4142	mm or %
top infill	width: 1.5	mm or %	spacing: 1.4142	mm or %
support material	width: 1.5	mm or %		
skirt	width: 1.5	mm or %		

Overlap

Perimeter overlap — Default: 100 % — External: 100 % — Gap Fill: 100 %
Solid fill overlap: 100 %
Bridge lines density — Min: 80 % — Max: 100 %
Infill/perimeters encroachment: 25% mm or %

Flow

Flow ratio — Bridge: 100 % — Above the bridges: 100 % — Top fill: 100 % — First layer: 100 %
Bridge type — Bridge flow baseline: Nozzle diameter % — Simulate Prusa 'no thick bridge': ☐
Cutting corners: 0 %