Project 22: Developing a 3D Printer for Functionally Gradient Soft Materials

ME 450 - Fall 2023
Final Report

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EXECUTIVE SUMMARY:

Functionally gradient soft materials (FGSMs) are getting more attention from the material science community. Their prospective applications in biomedical engineering make them an attractive area of investigation. The material design section of this research has had substantial advancements, but FGSMs are still facing challenges pertaining to fabrication and validation [2]. Despite the fact that making FGSM samples is already possible, verification protocols for their material properties are inconsistent. Without material characterization standards, FGSMs can not be used in industry, and their potential in the biomedical world is lost. The Experimental Soft Mechanics (ESMech) Laboratory at the University of Michigan intends to tackle this problem, and develop these material characterization procedures [1]. To help the ESMech lab with their objective, this project will develop the extrusion system for a 3D printer that can reliably produce FGSMs samples, specifically made out of silicone, with accurate material properties.

For concept generation, the team split the device into the pump/feeder, mixer, and extrusion subsystems. Utilizing divergent concept generation concepts and following the brainstorming “rules” outlined by Tom Kelley [33], the team generated a broad range of potential designs (Appendix A). Stakeholder interviews and a literature review, coupled with convergent concept selection methods, such as gut checks and morphological charts, were utilized to organize and narrow prospective design solutions to the top four for each subsystem. Pugh charts were utilized to evaluate solutions against one another, resulting in the top solution per subsystem. This leads to a design utilizing motor syringes, an impeller static mixer, and a tapered nozzle to accompany the frame of the Prusa MK3S+ that will serve as the foundation for the printer.

An initial engineering analysis was conducted. This involved using finite element analysis and *SOLIDWORKS* flow simulations to simulate the selected mixer design. An alpha design prototype was then constructed using results from the concept generation process, and initial empirical testing was performed. Testing and verification with respect to the engineering requirements and specifications was done to gauge the overall performance of the design. The mixer concepts showed promising results, while the motor syringe system demonstrated a lot of potential, but did present some challenges. The high pressures from the syringes created a moment with the motors, and caused bending in mounting plates. To solve this, the motors have to be repositioned and the plates have to be manufactured out of metal. Additionally, controls and resolution have to be improved through both a transmission system and firmware to achieve good smooth gradients in all three dimensions. Overall the design and first iteration of the printer was a very good first step towards a final product, and the ESMech Lab will be able to continue working on the printer design to finalize all necessary details, before starting with their research into functionally gradient soft materials.

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ABSTRACT

Gradient soft materials have exciting potential in biomedical applications; however, challenges still exist in terms of their fabrication and validation. This project aims to design a 3D printer capable of reliably producing samples of silicone rubber with gradient material properties. The design will focus on the pumping and extrusion subsystems, with the addition of controls adaptation. These samples will be used to develop standards and protocols for material characterization to be used in future applications. The initial design shows potential, but design iterations are required for performance optimization.

PROJECT INTRODUCTION

The project is sponsored by Jon Estrada, an assistant professor in the mechanical engineering department at the University of Michigan. Prof. Estrada leads the Experimental Soft Mechanics (ESMech) Laboratory, whose research efforts are closely aligned with the objectives of the project. The primary mission of the ESMech Lab research team is to characterize and predict behaviors of complex soft materials with the use of 3D experimental measurements [1]. Joseph Beckett, a Ph.D. student and member of the ESMech Lab will additionally help us with the research. This project exists to aid the ESMech Lab in their research of soft materials. The development of a fabrication method to produce soft materials would facilitate the lab's efforts. Specifically, the ability to produce complex materials with customizable properties would aid in the Lab's experimental testing and measurements. In addition, the sponsor would like to further explore the fabrication of functionally gradient soft materials (FGSMs). These materials have increasing interest, yet there is still a lack of a comprehensive understanding of their properties.

Functionally gradient soft materials are being actively explored for their use in biomedical applications. Although notable strides are being made in the design of these materials, there still exist current challenges in terms of fabrication and validation. Samples of functionally gradient soft materials can currently be produced, however, protocols to validate the material properties of the produced samples are not yet established [2]. A cost-effective and reliable fabrication method is needed to study these materials effectively [3].

This project's objective is to develop a functional prototype that can successfully print FGSMs, including materials like silicone rubber. This prototype will be used to establish a standardized protocol to verify the mechanical behavior of the printed materials. This requires that the prototype can reliably reproduce control samples with varying complexity and material properties. The team will work on developing controls/coding for the printer to dynamically adjust such desired material properties. The team will use the *Original Prusa i3 MK3S+* [4], a thermoplastic filament 3D printer, for its base and gantry system. This printer comes as a kit to be assembled, which makes it easily customizable. The Prusa i3 was chosen due to the availability of open-source hardware and firmware that can be utilized to configure the controls.

The prototype will consist of a modified version of this printer so that it can print gradient soft materials rather than plastic filaments. Therefore, emphasis will be placed on creating an original nozzle and mixing system that can properly extrude soft materials.

The project's success will be determined by the team's ability to first, produce a functional prototype, and second, validate the prototype's reliability through material testing. Therefore, the project can essentially be split into a developmental phase and a testing phase. The project will be successful if certain specifications are met for both the development of the device as well as the validity of the printed materials.

BACKGROUND AND INFORMATION SOURCES

Gradient Materials are commonly found both naturally and synthetically. Some examples of naturally occurring gradient materials included bone, teeth, skin and bamboo trees [5]. The gradient interface of these materials results in a smooth macroscopic transition of properties from one material to the other. This feature allows gradient materials to be designed with properties in desired quantities and locations. For example, gradients of composition, structure and specific properties can be engineered in a preferred direction [6].

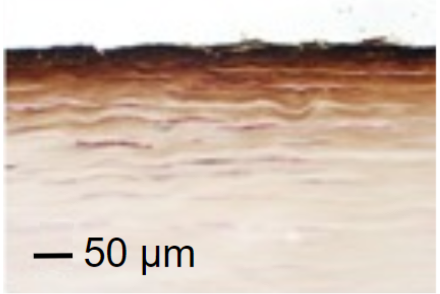


Figure 1a. Visualization of tendon-bone mineralization in the human body[7].

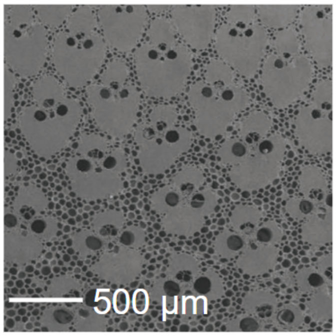


Figure 1b. Visualization of the porosity gradient in Moso bamboo[8].

One subset of gradient materials are Functionally Gradient Soft Materials (FGSMs). These soft materials are synthetically produced and have elastic moduli on the order of kPa to mPa [9]. These materials have important design applications from soft robotics and electronics to impact absorption and biomedical constructs and devices [10]. Silicone-based polymers are a soft material of particular interest due to their important material properties such as their excellent flexibility, resilience, adaptability, biocompatibility and thermal and chemical resistance [11].

Additive manufacturing methods have emerged as the most promising choice for producing complex FGSMs [9]. 3D printers, in particular, allow geometric complexity and customizability that is not available in other fabrication techniques [2]. Creating complex parts in 3D printers comes at no added cost, unlike other methods. For example, parts with hollow interiors, undercuts and internal channels are not possible with injection molding, pressing or casting without using multi-piece molds. 3D printing is now a widely implemented method of manufacturing, particularly for research applications, prototyping and limited-run parts. 3D printers typically use feedstocks of hard thermoplastics, but there is increasing interest in incorporating other materials to utilize their functional properties. 3D printing of soft, elastomeric materials has the potential to increase accessibility while decreasing the cost of customizable biomedical devices [2].

However, some unique challenges remain for the widespread production of 3D-printed FGSMs. One such challenge of multi-grade material printing is that different materials require different printing parameters for optimal output [12]. Therefore, 3D printers must be modified according to the specific material inputs. Another challenge is the difficulty in mixing and post-processing of materials. For example, mixing of two-part silicone resins requires meticulous mixing to avoid disproportionate mixing, trapped air bubbles and uneven curing [12]. In addition, silicone materials have slow cure speeds which constrain their fabrication [13]. A final barrier in the production of 3D-printed FGSMs is coming up with suitable standards. Currently, no ASTM or similar standards are prescribed for these materials. Soft material 3D printing requires precise standards for their application in medical devices, yet they do not presently exist [12].

BENCHMARKING

Currently, the commercially available 3D printers for soft materials are quite limited, with high price tags ranging from $24,000 to over $100,000, as detailed in Table 1 below. Despite their high costs, the printer specifications such as the build platform, print speed, and position accuracy remain comparable to lower-cost thermoplastic printers. This project aims to use the Prusa i3 MK3s+ thermoplastic printer as a structural basis, which will be converted to print soft materials [4].

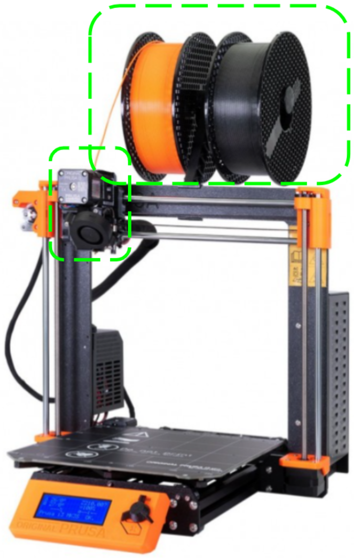


Figure 2. Prusa i3 MK3s+ thermoplastic printer with default filament extrusion module[4]. The components encompassed in the green dashed line are the extrusion module and material supply.

As seen in Table 1, the Prusa i3 printer comes at a fraction of the cost compared to the three showcased commercially available soft material printers. Furthermore, it outperformed these printers with a higher print speed of 200 mm/s. Creating an affordable prototype is critical to increasing the accessibility of complex soft materials.

Table 1. Summary of relevant benchmarks for different Soft Material 3D Printers

Supplier **3D Printer**	**InnovatiQ**: LiQ320[14]	**Lynxter**: S600D [15]	**Deltatower**: Delta Tower Fluid[16]	**ME 450:** Prusa i3 MK3S+ [4]
Price ($)	$120,000	$50,000	$24,000	$650
Material	3335 Liquid Silicone Rubber	Silicone RTV1 34/57	Many fluid options	Thermoplastics (PLA/ABS)
Build Platform (XxYxZ)	250x320x150mm	Ø360x600mm	445×445×400 mm	250×210×210 mm
Print Speed	10-150mm/s	150mm/s	150 mm/s	200mm/s
Position Accuracy	±0.2mm	±0.1mm	-	±0.3mm
Nozzle Options	0.23,0.4,0.8mm	0.20-1.60mm	0.06-2 mm	0.4mm

The team currently has access to a custom multi-material silicone direct ink-writing (DIW) printer as made available through the efforts of James Lorenz, a University of Michigan graduate student. The DIW printer has great advantages in multi-material printing due its novel extruding system that extrudes silicone inks out of nozzles to form a printed silicone fiber [9]. The availability of this printer will serve as an important resource for the development of the project's prototype. This DIW printer features a novel mixing device for 3D printing silicones as seen in Figure 3 below.

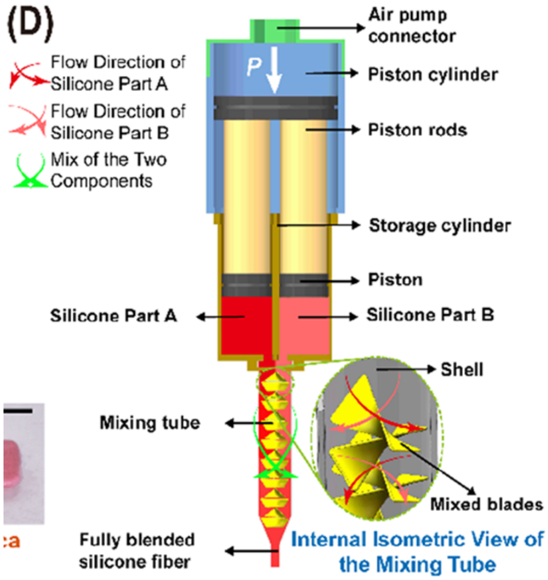


Figure 3. Novel 3D mixing device for 3D printing silicones. This mixing device uses an air pump to apply pressure to extrude two components of silicone rubber into a mixing tube. This mixing tube features curved mixing blades to continuously cut the fluid for complete mixing. Finally, the mixed silicone ink will be extruded out of the nozzle to steadily print the desired material mixture [11].

The developmental phase of the project centers around creating an extruder/nozzle system, while using the Prusa i3 for its frame and gantry system. Therefore, it is likely that James Lorenz's mixing device will be utilized as a reference in the prototype.

DESIGN CONTEXT

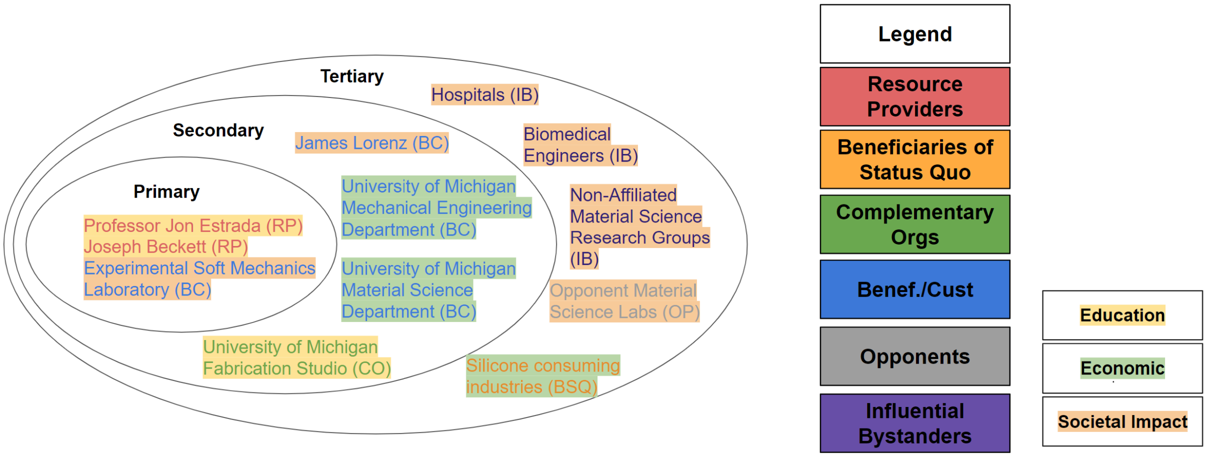


Figure 4. Stakeholder map and legend for the development of a 3D printer for FGSMs. This visual distinguishes stakeholders between primary, secondary, and tertiary tiers, and color codes each with their primary ecosystem category. Highlighting colors depict each stakeholder's design context.

The stakeholders for this project range from individuals with direct influence, to broad markets that may be impacted in the coming years (Figure 4). The primary stakeholders include Professor Jon Estrada, Joseph Beckett, and the ESMech Lab.

Professor Estrada is a resource provider, the sponsor for this project, and the head of the ESMech Lab. As part of the development of Professor Estrada's grant proposal for the National Science Foundation, this project will be used directly by the ESMech Lab for material characterization research [9]. As part of the proposal, Professor Estrada plans to assist in guiding the safety of noninvasive surgical procedures to the benefit of society by utilizing the research that this project enables.

Joseph is a Ph.D. student and resource provider working for the ESMech Lab who volunteered to assist the design team. As a member of the ESMech Lab, Joseph researches advanced full-field experimental techniques developed to measure the deformation and fracture of soft materials and structures [1]. Due to the nature of this research, he will regularly utilize the final design to produce samples for their research. Through this, they are able to provide additional insight into their current use cases and potential future uses. Similarly, the ESMech Lab serves as a beneficiary of this project due to being able to utilize the device in experimental research as needed.

Broadening the scope, the secondary stakeholders consist of individuals and departments affiliated with the University of Michigan who interact with the project in some way, but may not be directly impacted. This includes James Lorenz and the University of Michigan Mechanical Engineering Department, Material Science Department, and Fabrication Studio. As mentioned previously, James developed a prototype 3D printer for soft materials (Figure 3), similar to the objective of this project. Expanding upon James' preliminary work, this project aims to further improve the design and thus benefit James as well. The University of Michigan departments are beneficiaries of this project as they may utilize the device or construct additional devices to suit their needs. Less directly, the Fabrication Studio serves as a complementary organization to this project. Currently, the studio has standard 3D printers that may be used by individuals and organizations affiliated with the university. As this project aims to enable further research and utilization of functionally gradient soft materials, it is logical to implement an additional device for use in the Fabrication Studio.

Tertiary-level stakeholders include bystander industries and communities, potential opposition, and beneficiaries of the status quo. These stakeholders are not involved in the project, but may be impacted as time goes on. Hospitals, the biomedical community, and non-affiliated material science research groups are examples of bystander industries and communities. While the project may not impact them currently, they may utilize future iterations of the final design that are catered to their specific use case.

As research can sometimes be competitive between institutions, research groups not affiliated with the University of Michigan may oppose this project. If the project succeeds and allows for further advancements in research, additional funding and grants may be directed away from the opposing research groups. Silicone-consuming industries, such as the one for industrial adhesives, may benefit from this project not solving the problem at hand. If successful, an advanced industrial adhesive with a complex material gradient may potentially be developed and serve as a competitor. Thus, some of these industries are beneficiaries of the status quo.

As mentioned previously, functionally gradient soft materials occur naturally in the human body [5]. Due to there being very limited production methods and no protocols for the verification of material properties, synthetic implants that mimic natural materials are not able to be fully utilized. Leveraging a cost-effective and verifiable method of creating such materials would allow for custom implants to be produced that can be tuned to the exact needs of each individual[3]. Additionally, these implants may reduce the complexity of reconstructive procedures.

In the case of vocal fold reconstruction, the current method of replacement is a very complex procedure that requires the "anastomosis of the superior thyroid artery, jugular vein, and four nerves (two recurrent and two superior laryngeal nerves) [17]." If synthetic replicas of vocal folds were to be produced and verified, as shown in Figure 5 below, this procedure would greatly reduce complexity and reduce the risk of potential complications. This project aims at enabling the creation and verification of such materials.

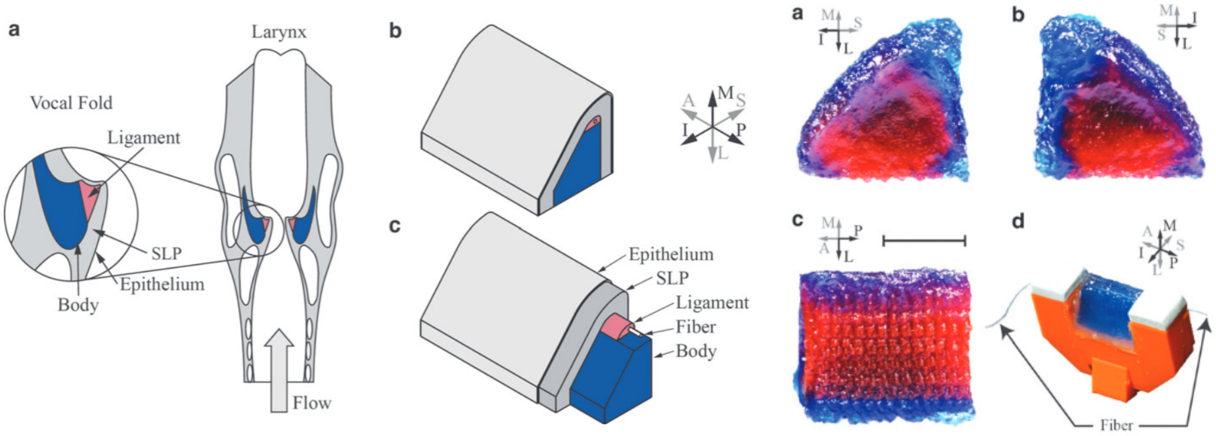


Figure 5. Illustration depicting vocal fold location and tissue layers (left) and sample printed silicone vocal fold replica with applicable gradient (right) [18]. While these silicone vocal folds were able to be printed, there was no method to verify material properties. If they were verified, these may be utilized as part of an alternative procedure to replace vocal folds.

Due to this project focusing on establishing a foundation for research advancements, direct societal impact is difficult. Given this, Professor Estrada also hopes to utilize educational impact through research as a conduit to enable further societal impact. This advancement in research of material mechanics will improve the accessibility and useability of functionally gradient soft materials for other fields, such as biomedical. These advancements may serve as a guide for improving the safety of nonsurgical procedures and provide accessible alternative medical solutions [12]. Thus, while social impact may not be ranked as a direct objective, it accompanies the prioritization of educational impact over the prioritization of profit and environmental impacts.

As this project is focused on allowing for research advancements, the design of the device will cater to use in research applications. For other industries and fields, the device will most likely need to be modified for the specific use case. This would result in extended implementation time, which may cause an initial negative societal impact. However, the design of the device will ideally require minimal modifications for these implementations, thus minimizing the initial negative spike. Through this, it can be determined that while the order of the sponsor priorities may affect the overall design, it will result in minimal negative social impact, if any at all.

For this project, intellectual property has only impacted which sources may be referenced and cited. This project does not involve any contracts or IP transfers, and thus has not been a focus. However, if deemed applicable by the design team, the extrusion mechanism design for the device may be protected under a patent. As the rest of the device design will be utilizing open-source resources, intellectual property protections will not be applicable. The intellectual property that is created through this project will be owned by the members of the design team.

When manufacturing and developing the project design, existing 3D printer hardware will be used when applicable. This allows for a sustainable path of repurposing existing materials that may have otherwise gone to waste. Additionally, the firmware utilized by the device will be open-source, thus allowing others to repurpose and customize it to fit their needs [4].

A primary requirement for this project is reliability and repeatability, which requires the device to have a long lifespan. If this extended lifespan is accomplished, it will reduce the need for additional materials to be consumed or wasted, thus allowing for physical sustainability. For the disposal of the project design, many of the materials and components may be recycled or repurposed. This includes items such as the metal frame and plastic components of the printer, the motors, the pumps, and electrical wiring.

Naturally, this project design will not be fully sustainable. While existing hardware may be leveraged, this design will still require additional material to be utilized and then manufactured. Through these manufacturing and machining processes, pollutants and waste may be emitted. Furthermore, when using the device and printing soft materials, it may be difficult for the Components such as printed circuit boards, timing belts, and tubing are also difficult to dispose of sustainably. This would further contribute to the overall waste of the device when disposed of.

However, increasing energy efficiency and the lifespan of the design will result in increased sustainability during use. The main optimization process to ensure efficient energy usage would be the optimization of print paths. This will allow for unnecessary motor movements to be reduced, thus requiring less energy, but will take additional time. To increase the lifespan of the design, additional supports or high-quality materials may be used, with a tradeoff being higher manufacturing costs.

There are sustainable advantages to this manufacturing method, over the traditional methods used for making soft materials samples. The usual injection molding process requires custom-made molds to be made and discarded constantly, especially in a research setting like the ESMech Lab. Additive manufacturing eliminates the need for molds, and thus reduces considerably the amount of waste material resulting from studies and work on functionally gradient soft materials.

For this project, ethical dilemmas centered around device cost and limited production capabilities of the device may be encountered. During the background research and benchmarking for this project, it was found that current soft material 3D printers can cost tens of thousands of dollars (Table 1). This high cost restricts their usage significantly and can pose a barrier to communities that are unable to procure such funding. By utilizing an existing 3D printer as a foundation and performing the necessary modifications, the overall cost will be reduced tremendously, allowing for it to be much more accessible. If the device has limited production capabilities and is unable to produce complex material structures, it may also exclude certain groups and use cases. To address this and improve accessibility and inclusivity, user requirements and specifications have been established. If these specifications are followed, the risk of potentially excluding users is greatly reduced.

The personal ethics of the design team align well with the professional ethics that the University of Michigan expects to be upheld. The mission of the University of Michigan includes serving the people of Michigan and the world through applying knowledge and creating to enrich the future [19]. Through this project, the design team aims to design and create a device that allows for a fundamental advancement in the research of material mechanics. Ideally, this project will lead to global accessibility of affordable alternative medical solutions and enable further enrichment of the future through advanced material research and development. This would also align with future employers, however, employers will also aim to profit off of designs. This aspect aligns less with the personal ethics of the design teams but is expected due to the nature of society.

For this project, the project sponsor is an end user, and thus power dynamics are fairly simple. The project goal is to design a device that is capable of producing material samples as specified by the end user. While the sponsor may establish certain requirements and propose potential solutions, the end design solution is decided by the team.

Between team members, each member has a focus area for the project, but everyone has equal footing in design decisions. This allows for various viewpoints to be heard and considered in the design process, resulting in a better overall solution.

In order to have the final design be as inclusive as possible, it is important to establish potential use cases for the device that are outside of the backgrounds of the design team. If this does not occur, the final design may be heavily focused on limited use cases and restrict overall performance and success. In order to address further unidentified inclusivity problems, it will be important to maintain contact with a diverse group of stakeholders, be open to external ideas and use cases, and look at the project from a viewpoint outside of each member’s technical background. Weekly meetings with stakeholders, especially the project’s sponsor, and constant email communication with other interested stakeholders could be very helpful to guide the design solution in the best way possible.

There are no intellectual property protections applicable for this project. The design of the printer is not part of the ESMech Lab’s research proposal, so it is not considered protected property. However, the design and prototype resulting from this project will be owned by the ESMEch Lab, and not the students undergoing this project.

At the start of the semester, the team met with the librarian, to talk about what information gathering approaches would be best for this project. This meeting helped the team determine that, because this project revolves around research and experimentation, the best way to gather information would be academic papers and primary sources connected to similar research topics. Academic tools like ScienceDirect, Wiley Online Library, and Springer were used to undergo the literature review required for this project. Additionally, the team also used primary sources like Professor Estrada, Joseph Beckett, and James Lorenz to gather information about material science, mixing, and silicone printing for this project.

The main challenge the team encountered with information gathering was not actually finding sources, but truly understanding the knowledge those sources were providing. This project involved a lot of advanced fluid dynamics, material science, and controls sciences, and the team did not have all the necessary experience or knowledge to tackle those topics head on. Thus, to overcome this challenge, the team relied heavily on primary stakeholders and experts to understand what some sources were saying. Professor Estrada, Joseph Beckett, and James Lorenz were vital not only as primary information sources, but also as "translators" for research papers and academic documents.

USER REQUIREMENTS AND SPECIFICATIONS

To determine user requirements and specifications, the team met with the project sponsor to determine what requirements would be most, and least, important for the success of this project. Since the 3D printer resulting from this project will be used in a unique research environment, all requirements and their priority were dictated by the ESMech Lab and Professor Estrada. High reliability and material properties accuracy are the basis of sponsor requirements. After reliability and accuracy, high functionality follows in level of priority. The range of functional gradients in space the printer is able to produce will determine how well the design performs, in terms of sponsor research needs for testing and material characterization. There are no existing codes or standards for a project of this kind. Part of the objectives of the ESMech Lab with functional gradient materials is to develop testing and material characterization standards, so the technology developed during this project will help develop said standards.

This project's requirements and specifications have to be divided into two categories: device and product or print. Because the specific objective of this project is to develop a functional prototype that can successfully print FGSMs, in order to establish a standardized protocol to verify the mechanical behavior of the printed materials, some of the requirements coming from the project's sponsor are for the printing product, and not the 3D printer, the device actually being designed. After describing print requirements, these will have to subsequently be "translated" into device requirements to follow during the project. Thus, all project requirements will be divided in this report into the two categories of device requirements, and print requirements. Table 2 shows device requirements and specifications, in order of project priority:

Table 2. Device requirements, specifications, source, and justifications.

Requirement Number	Requirement	Specification	Source
1A	Reliability and Repetition	Hardness and Local Geometry Coefficient of Variation ≤ 10%	[20]
2A	Material Premixing	Relative Mixing Index ≥ 0.7	[21]
3A	Printer Dimensions	Frame dimensions ≤ 500 mm x 450 mm x 750 mm	[22]
4A	Print Dimensions	Print dimensions ≤ 40 mm x 25 mm x 25 mm	[22]

The driving device requirement, requirement 1A, is reliability and repetition. Being able to consistently produce intended products is vital for the research environment this printer will be used. The coefficient of variation (CV) is often used to describe manufacturing process reliability [20]. CV can be calculated with Eq. 1:

$$CV = \frac{\sigma}{\mu} \quad (1)[23]$$

where σ is the standard deviation, and μ is the mean.

For this project, the CV of the hardness and a local geometry measurement will be used as an evaluation of repeatability, based on sponsor requirements for research, and the reasonable ability to test these features with the available resources in the ESMech Lab. The pumping, mixing, and extrusion systems have to be accurate and consistent. All systems will have to be easy to control and tune-up. A maximum CV of 10% for these features is considered to be acceptable in the manufacturing industry [20]. This target number is reasonable but will be challenging, considering additive manufacturing usually falls short of this objective [20].

Requirement 2A highlights the importance of effective premixing of the two-part silicone solution before printing. An almost homogeneous mix of the two intended phases is needed, in order to actually produce the intended material qualities. There are many mixing efficiency quantification methods, but the one that would best suit this requirement is the relative mixing index (RMI). The RMI uses imaging analysis to determine how well-mixed a certain solution is [24]. To calculate mixing efficiency, RMI uses the ratio of the standard deviation of pixel intensities in a cross-section of a mixed solution (after printing), and the standard deviation of pixel intensities in an unmixed state (before going into the printer). RMI is then calculated with Eq. 2:

$$RMI = 1 - \frac{\sigma}{\sigma_o} = 1 - \frac{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \left(I_i - I_{avg}\right)^2}}{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \left(I_{oi} - I_{avg}\right)^2}} \qquad \text{(2)[19]}$$

where σ is the standard deviation of pixel intensities in a cross-section of a mixed solution, σ_o is the standard deviation of pixel intensities in an unmixed state, N is the pixel number, I_i is the pixel intensity of the mixed solution, and I_{avg} is the average pixel intensity.

As a basic set up, a smartphone camera and a tripod will be used to get the images for analyzing. Past research has shown that mixing fluids with low Reynolds numbers, like silicone, usually results in an RMI of around 0.6 [21]. However, for the purpose of this project, the mixing efficiency has to be higher in order to produce the desired material properties. Thus, the specification for requirement 2A will be an RMI of 0.7 or higher. This specification will be challenging to achieve, based on the aforementioned research, but has to be accomplished for a successful project. The RMI can be measured through many means, but Matlab imaging analysis would be the most accessible for this project.

As stated before, this project will use a Prusa i3 MK3s+ printer as a structural basis. Because of that, requirements 3A and 4A in Table 1 constrain the printer design to the frame and printing bed dimensions of the skeleton printer. A flawless integration of this project's design with the base printer will depend on abiding by these size constraints. These two requirements' importance is just based on the base printer being used, however, the success of a generic printer of this kind would not depend on these dimension constraints. Specifications 3A and 4A will be verifiable during the initial product design and with simple dimension measurements.
Table 3 shows print requirements, their respective "translation", and specifications, in order of project priority:

Table 3. Print requirements, device translation, specifications, source, and justifications.

Requirement Number	Print Requirement	Device Translation	Specification	Source
1B	Minimize Gas Content	Minimizing Introduction of Bubbles	Bubbles introduced during mixing have a diameter ≤ 175 μm	[25]
2B	Functional Gradients in Two Directions	Two Degrees of Freedom	Printing path is controllable in X and Y directions as concentrations vary	Sponsor
3B	Wide Range of Functional Gradients	Variable Mixing Ratios	Mixing ratio can be intentionally changed by ≤ 10% during printing	[26]

The driving device requirement, requirement 1B, is minimizing the gas content in the print. When dealing with two-part silicone elastomers, final products are prone to air bubble contamination, which affects the overall mechanical properties of the specimen [16]. Gas bubbles are usually introduced during mixing, and are a result of two different factors: the difference in pressure gradients induced by the mixer and the pressure gradient of the gas (air), and how high are the fluid flow rates [28]. Design decisions on the mixer type and operation will need to be made based on this information. Controlling these two parameters will determine how much gas introduction there is into the system. Because print products from this project will be used for material characterization, minimizing gas content in the prints is very important. As a device requirement, this means minimizing the introduction of bubbles during the solution-mixing process. The vast majority of gas phase contamination - in the form of air bubbles - is introduced during the mixing of two-part silicone elastomers [28]. Based on sponsor experience with these kinds of materials, air bubbles significantly disrupt the local material properties of a silicone specimen when they are visible to the naked eye. Thus, the specification for this driving print requirement is that the mixing system should be able to introduce bubbles with a diameter less than, or equal to, 175 μm, which is the maximum object length seen by the average human eye [25]. In this case, bubbles will be considered to be perfect spheres, so the bubble diameter is assumed to be the visible length. Achieving this bubble size target will be challenging, but feasible. Visual inspection of specimens done by all team members will be done to verify how the mixer design performs with respect to this requirement. It is imperative that the design does meet this specification, in order to produce the best research specimens possible. This specification will be able to be measured by simple visual inspection of samples produced.

As a second print requirement, and based on sponsor needs for research, products must have functional gradients in two directions in space. This leads to a simple device translation shown by requirement 2B: the printer must be able to work with two degrees of freedom in space. The specification for this requirement specifies that the printing path must be controllable in the X and Y directions as concentrations vary, where the X and Y directions are assumed to follow a right-handed cartesian coordinates system as shown in Figure 6:

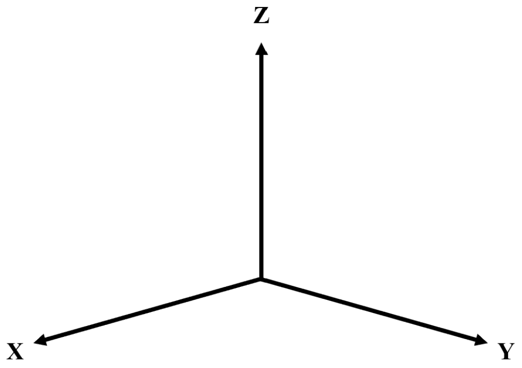


Figure 6. Reference coordinates system followed by requirement 2B. Figure made by the team members.

This is a very reasonable specification since the base printer the project is using already had these two degrees of freedom in space. The main problem in achieving this requirement will be with the print requirement, and the functional gradients, not with the device requirement.

Having a wide range of functional gradients available for printing will allow the ESMech Lab to do ample research on FGSMs, giving room for wider characterization procedures for these materials. Requirement 3B translates the need for a wide range of material properties to variable mixing ratios. Since the functional gradients of material properties will depend on the two-part silicone mixing ratio, being able to accurately transition between mixing ratios is very important. Based on past research on material properties for this kind of silicone elastomers, resulting mechanical properties are effectively modified with a 10% change in mixing ratios [26]. The system has to be able to change mixing ratios, specifically the volume output of each silicone component, with “steps” of less than, or equal to 10% of the current value. High-viscosity fluid flow systems are widely used in industry [29], so 10% volume output sensitivity is very reasonable in the context of this project. To verify the printer’s pumping system is outputting the desired mixing ratios, volumetric flow measurements could be made to tune up performance.

As a last print requirement, requirements 4B and 5B specify print features of less than, or equal to 0.5 mm. The intended testing methods - specifically using Magnetic Resonance Imaging - for the FGSMs produced by this project's 3D printer can constantly achieve a resolution of 0.5 mm [29]. This feature size requirement can be translated to a device requirement as a high printer resolution. Printer resolution is defined as the smallest detailed feature a printer can produce [30]. Previous research on the 3D printing of silicone elastomers has shown that printing speeds below 15 mm/s lead to silicone overflow on the printing bed, while speeds above 25 mm/s result in silicone droplets being deposited throughout the printing process. Additionally, the same research paper showed that nozzle diameters smaller than 0.51 mm lead to under-extrusion of silicone, and nozzle diameters larger than 0.6 mm resulted in over-extrusion of material during printing [16]. Thus, these two speed and nozzle diameter ranges will be used as specifications for the high printer resolution requirement. These values are typical in the additive manufacturing industry and are achievable. Both specifications for requirement 4B could be measured in the ESMech Lab through empirical testing.

All project requirements that must be met are presented in Tables 2 and 3. Nonetheless, Table 4 shows the one requirement that is just a "nice to have", meaning the final performance of the design does not depend on meeting this requirement, but it would ultimately improve the overall project outcome:

Table 4. "Nice to have" project requirement, with its specification.

"Nice to Have" Requirement	Specification
Design is organized and aesthetically pleasing	Wiring and electronics are managed and organized into 1 controlled location

A well-organized and aesthetically pleasing system is not required for the functional success of the 3D printer being developed for this project, but it would make it easier to work on in case maintenance is needed, and easier to handle in the workspace. Since the only components that could be loose for the 3D printer are the wires and electronics, having 1 controlled location for them as a specification ensures order.

Throughout the project, some of the user requirements and specifications had to be modified and/or eliminated. The specification for requirement 3A, *"Printer Dimensions"*, changed during the project development. The original specification called for frame dimensions of less than or equal to 500 mm x 500 mm x 450 mm. Because the concepts chosen for the pumping and extrusion subsystems required more space than expected, the project's sponsor approved a change to the specification, with new frame dimensions of less than or equal to 500 mm x 450 mm x 750 mm. Another change to requirements and specifications was the elimination of what used to be requirement 4B, *"Print features of less than or equal to 0.5 mm"*. To achieve this printing resolution, the design would require a transmission system, to reduce the volumetric output of the printer. However, the time constraints of the semester meant that the team would need to spend a significant amount of time designing the transmission system, leaving the rest of the project on hold. Thus, the team decided - with the sponsor's approval - to focus on producing a printer with a lower resolution, but within the time available for this class, and eliminate requirement 4B.

DESIGN PROCESS

So far, this project has been in the problem definition stage of its design process. The working time has been dedicated to understanding the problem with current FGSMs 3D printers, collecting the relevant information on how they perform, coming up with and prioritizing stakeholder requirements, and then translating those requirements into specifications. This initial stage is part of every structured design process, so no specific one has been used yet. However, based on project and sponsor needs, the design process model considered for this project is depicted in Figure 8:

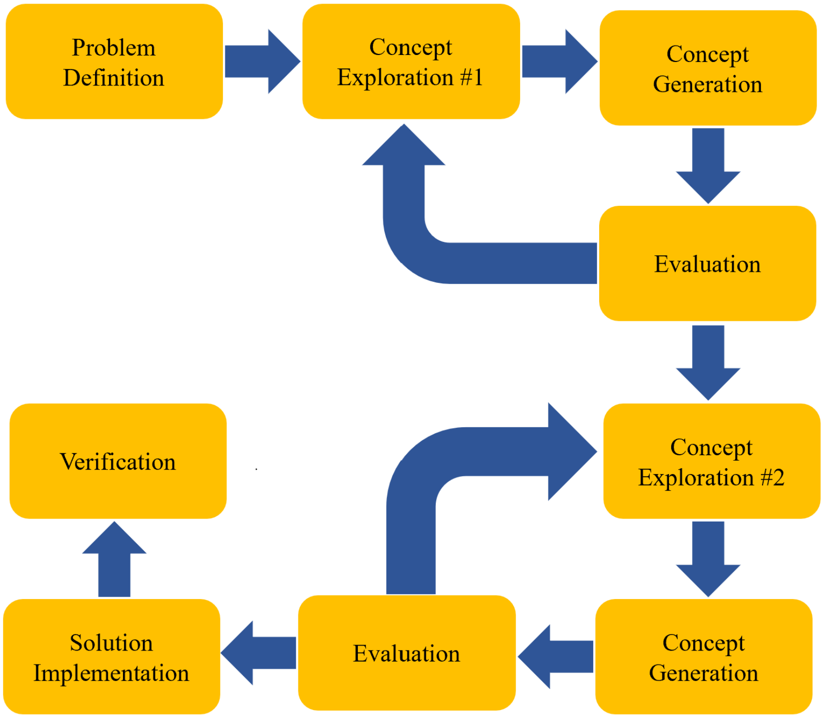


Figure 8. The design process model is predicted to be followed for this project.

The design process model depicts the iterative nature of the design process. It is important that the team continuously evaluates the progress of the project to make sure that the team's primary objectives and requirements will be met. The team will assess functionality through testing and sponsor feedback to ensure the design meets its intended purpose. In addition to evaluating if design concepts can properly meet requirements, the team will evaluate if they are feasible to be fabricated, are within the team's budget, and are in compliance with industry standards and regulations. This evaluation approach ensures that design concepts not only align with project requirements but also consider practicality, financial constraints, and the necessary safety considerations to ensure a successful project. A trigger for a redesign will typically take place if one of these factors is presumed to fail. Breaking the project down into smaller subcomponents will make it easier to undergo this iterative process by not having to do a complete overhaul of the design.

This project will focus on two main designs: mixing and extrusion systems, and pump/injector systems. Based on sponsor input, the pump/injector phase will not be able to begin until the mixing and extrusion systems have been completed. Both designs will go through iterative processes before being finalized, so each concept will have a cyclical nature until all requirements have been met, and the design is satisfactory. Subsequently, an implementation stage where a controller will be modified will take place. Thus, a combined model of both stage-based and activity-based models, as described by Wynn and Clarkson [31] seems to be the most promising for this specific project. The linear, stage-based component of this design model is shown from the clear, differentiated parts of the process that need to be completed before continuing with the process. However, within each stage, specifically the design development stages, there is an iterative process that follows an activities-based approach.

As stated before, there are already 3D printers for soft materials in existence. These designs present different solutions for this project's design project, the most important being the aforementioned DIW developed by James Lorenz (Figure 3). Because of this, a solution-based approach, as defined by Wynn and Clarkson [31], shows the biggest potential for success. During each one of the stages, a principal solution will be studied, and iteratively modified until it meets the engineering requirements.

The ME 450 design process model presented during the first day of class is somewhat similar to the one just described. Both use iterative methods to reach a final solution, relying on the cyclic approach to modify designs until they satisfy all requirements. However, the ME 450 design model is activities-based and problem-oriented, unlike the one predicted for this project. As stated before, this project requires each subdesign to be completed before the next one can be started, so there is a linear, non-cyclical component that the ME 450 does not have. Additionally, the ME 450 design model has a big emphasis on a thorough analysis of the problem before coming up with the initial range of solutions, which is different from the predicted approach for this project.

After starting the project, the actual design process differed slightly from expected. The team went through the first stage of concept generation and exploration, with which an initial overall design was produced. This alpha design was then translated into a digital prototype, and then a physical one, used for testing. Thus, the initial design process for this project followed a more linear approach, rather than the cyclical one described before.

With the physical embodiment of the design, the team started testing and exploring the general performance of the prototype. After finding areas of improvement, the information gathered during testing was used to iterate on the design, falling back on the cyclical design process predicted. The physical embodiment of the design changed the way the team approached the design process. Figure 9 shows an updated diagram of the overall design process followed during this project:

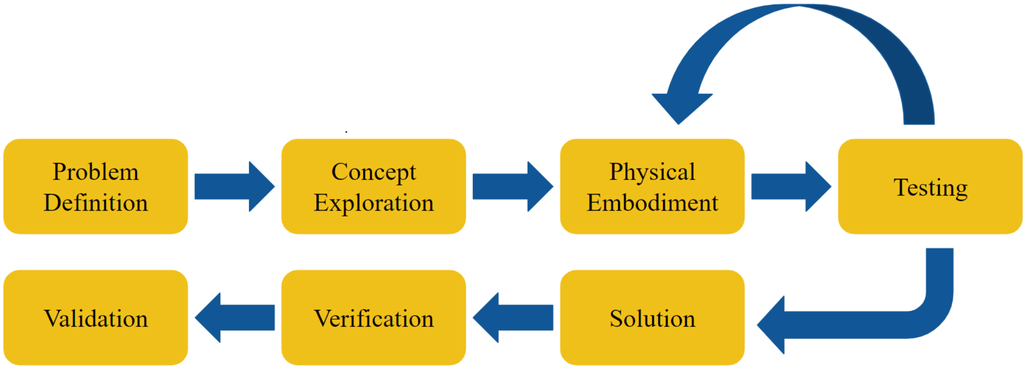


Figure 9. Design process followed during this project.

CONCEPT GENERATION AND SELECTION PROCESS

To begin with the concept generation stage of this project, the project's sponsor recommended a functional decomposition of the 3D printer to simplify and organize the design objectives. Following the ME450 Functional Decomposition practices outlined in the Concept Exploration Learning Block, the team decided to approach this task with a flow chart strategy. Figure 10 shows the resulting flow chart of the functional 3D printer:

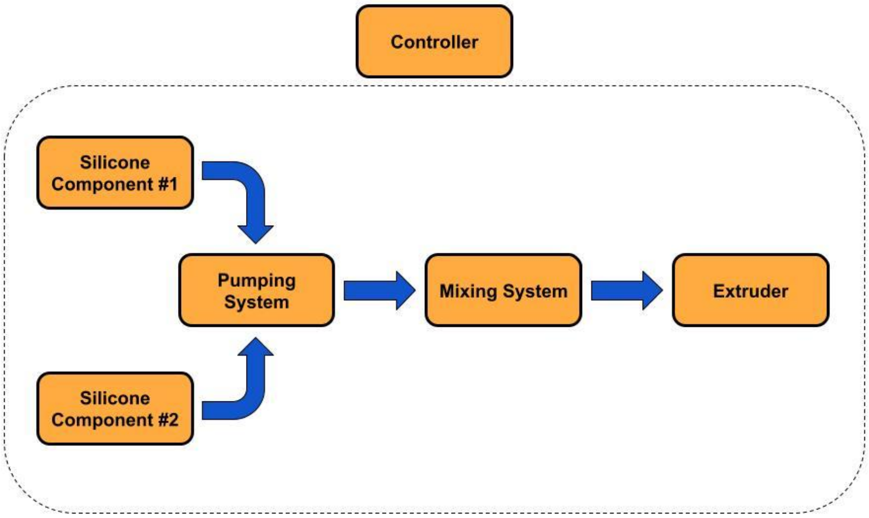


Figure 10. Process flow diagram for the overall design.

The process of printing starts with two main silicone components, with different mechanical properties, in separate containers. These two main silicone components will be displaced by a pumping system, which will drive the flow of silicone into a mixing system. Finally, the mixed silicone solution will go through the extruder, onto the printing bed. This whole process will be regulated by an overall systems controller.

For the mechanical design pertaining to this project, concept generation and selection stages will focus on the three subsystems seen in Figure 9: pumping, mixing, and extruder. Thus, the concept generation and selection stages for this project followed the structure seen in Figure 11:

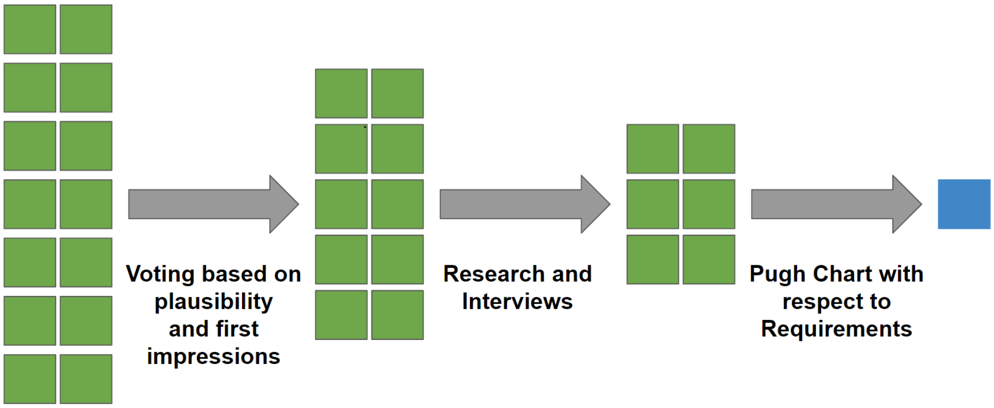


Figure 11. Concept Generation and Selection Process.

The concept generation stage for this project started with a rapid concept generation session, to come up with as many concepts for each of the subsystems as possible. Then, a group voting session was held to eliminate concepts based on plausibility and first impressions.With the remaining concepts, research and interviews were conducted with different stakeholders to get input on how to eliminate even more concepts from each sublist. Finally, Pugh Charts were developed based on the user requirements and specifications, stakeholder input, and external research to decide which one of the remaining designs for each one of the subsystems would make it into the alpha design.

The initial concept generation followed the brainstorming practices proposed by Tom Kelley [33]. Three brainstorming sessions were held, one for each subsystem. For each one of them, all team members proposed as many concepts as possible, no matter how wild or unfeasible they seemed. Sketches and diagrams from the Concept Exploration Learning Block were used to begin, but as more concepts were proposed, new, different ideas were suggested based on other team members' input. Figure 12 shows three designs resulting from this brainstorming session that exemplify the approach taken:

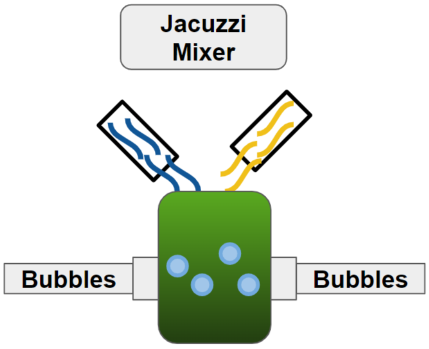


Figure 12a. Jacuzzi mixer concept for the two silicone components.

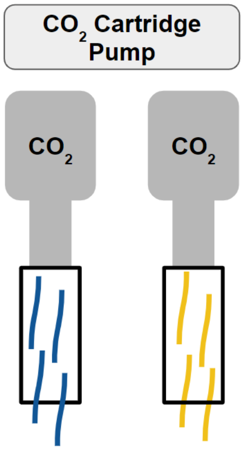


Figure 12b. CO_2 cartridges pumping system, using pressure differential.

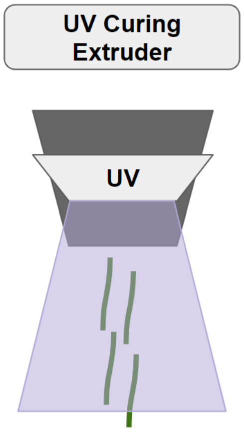


Figure 12c. UV flashlight attached to nozzle to enhance silicone curing.

The jacuzzi mixer concept utilized air bubbles to displace fluid within a container, to mix two different silicone concepts with the flow. The team decided to eliminate this concept, based on the fact that having jacuzzi bubbles as a mixing method would only not be very effective, because of silicone's high viscosity, but would also introduce gas into the mixture, a counteracting measurement to one of the project's driving requirements.

The CO_2 cartridges pumping system would use widely available pressurized CO_2 cartridges to, when opened behind the silicone components, would apply pressure to the fluids to displace them forward. This concept was eliminated during voting because of the lack of repeatability, the introduction of gas bubbles into the system, and the environmental consequences of using CO_2 throughout a print.

The UV nozzle concept would point an UltraViolet (UV) light flashlight to the silicone extrusion coming out of the nozzle, to speed up curing time and quality. The team decided to keep this concept on the list, based on high engineering feasibility.

All concepts for the pumping system resulting from the brainstorming session can be found in Appendix A, with concepts provided by each team member.

The research and interviews stage involved talking with stakeholders, interested parties, and a thorough literature review to evaluate all concepts left after the voting session. Figure 13 shows the main resources used throughout this part of the concept generation process:

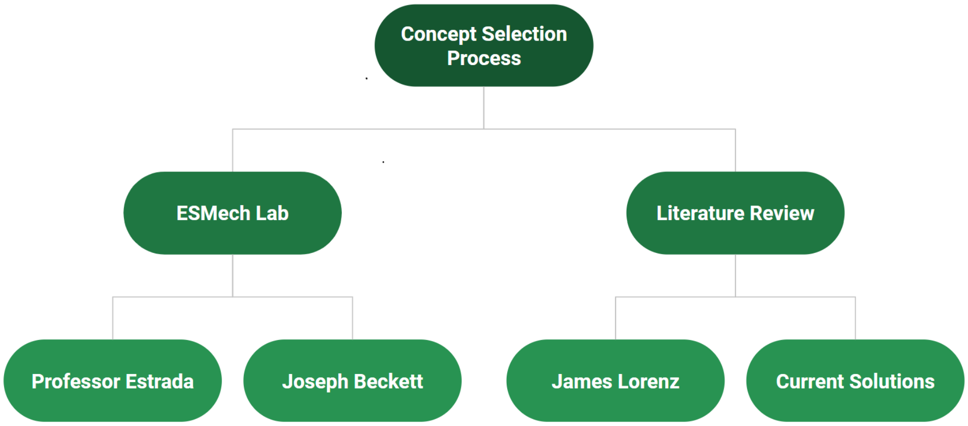


Figure 13. Stakeholders, interested parties, and general literature review consulted during research and interviews concept generation and selection process.

As the project's sponsors, and the main interested parties, the ESMech Lab, and specifically Professor Estrada and Joseph Beckett, were very important during this stage of the concept generation and selection process. From the literature review side, two main resources were utilized: current soft materials 3D printing solutions, and James Lorenz. As previously discussed, in Table 1, there are current solutions to soft materials 3D printing, specifically silicones, that provide information to evaluate how effective the remaining ideas for mixing, pumping, and extrusion could be. Part of the literature review was used to evaluate how current solutions compare to the remaining concepts [2][11][18]. Most solutions found match the remaining concepts in one way or another. The literature review also helped with one of the most complicated factors in this project: the fluid mechanics of the silicone and its behavior inside the mixing system [21][27][39]. This part of the literature review highlighted how complex the mixing of highly viscous fluids is. Reducing the pressure drop within the mixing system is vital, because of how hard it is to effectively displace these kinds of fluids. Different kinds of mixers also perform better or worse with respect to air bubble introductions. The more a mixer displaces air with the silicone, the more likely the development of gas bubbles. Additionally, James Lorenz and his work on soft materials 3D printing served as a main source of knowledge. During a meeting with the Michigan grad student, the team was able to gather a lot of information, ask questions, and learn about what the best design approach for each one of the subsystems would be. After finalizing all interviews and research, the team diluted the concept list for each one of the printer components to four, final design ideas for each one of them. Table 5 shows a morphological chart of the twelve different concepts:

Table 5. Morphological chart containing the final four solutions for each printer subfunction.

Subfunction/Component	← Solutions →			
Pumping System	Electric Pump	Motor Syringe	Gravity	Archimedes Screw
Mixing System	Dynamic Mixer	Tank Baffles	Impeller Static Mixer	Magnetic Spinner
Extruder	Tapered Nozzle	UV Curing	Variable Diameter	Syringe

Electric pump refers to any kind of pump that uses an electrical current for power and displaces fluids as work [34]. This kind of pumping system is widely used in many industries and is highly available, so multiple options for electric pumps could be evaluated to find the best choice for this project. A motor syringe, or syringe pump, "is a motor-driven precision pump that uses one or more syringes to deliver precise and accurate amounts of fluid" [35]. Motor syringes are common in laboratory settings, because of their low cost and reliability, and because they utilize simple motors, transmission systems, and syringes, they are also highly customizable. A gravity-fed pumping system would not actually be a pumping system, but it would eliminate the need for "extra" components to displace the silicone into the 3D printer. Finally, the Archimedes Screw pump is a kind of positive displacement pump that uses the air cavities of an enclosed screw to force a fluid in one direction [36]. Positive displacement pumps, and the Archimedes screw, are relatively simple, and widely used, and can accurately move a specific amount of volume.

The dynamic mixer concept just refers to any kind of mixing system that mechanically rotates within a fluid to mix it around [37]. This kind of mixing system is extremely common, from the kitchen to the paint industry, and would be a simple option for this subsystem. Tank baffles are a type of static mixer, and are commonly used in chemical reactors due to their efficiency and simplicity [38]. The impeller static mixer is, as the name suggests, another type of static mixer.

This mixer is known for its mixing efficiency and was studied and used by James Lorenz [39]. The concept of a magnetic spinner "uses a rotating magnetic field to move a stir bar around in liquid samples. The movement of this stir bar mixes the samples thoroughly with rapid movement and agitation" [40]. This type of mixer is widely used in laboratories and for many different kinds of solutions.

A tapered nozzle is a simple kind of nozzle, in which the inlet diameter is larger than the outlet diameter. Very common in the medical industry at the size scale of this project, which makes it readily available for use. The UV curing nozzle would involve, as explained before, the addition of a UV flashlight at the end of the extruder to accelerate the rate of curing of the silicone on the printing bed, which would give the user better printing freedom with respect to time and speed. A variable diameter nozzle would give the user the option to increase or decrease the feature size of the print, depending on how much resolution is needed for each location. This would decrease printing time and increase usability. Finally, a simple syringe for an extruder could simplify the extruder design, and decrease cost.

Following the concept generation process, the team's next step is to select which concepts will be implemented into the alpha design. This selection process consisted of creating a ranking system to pick the best solution from each of the three printer subfunction categories of the morphological chart. The ranking system was modeled after a Pugh Chart where the team could compare and evaluate multiple design options against a set of criteria categories. The team found that using a structured approach helps to ensure that the solution that best meets the key design requirements will be the one selected to be brought forward into development. Although the final design will continue to be iterated on throughout the development process, the selection process will allow the team to focus on developing this single concept rather than multiple potential solutions. The team spent ample time in their decision-making through the selection process to avoid prematurely fixating on a single design concept.

The Pugh Chart for each printer subcategory contains different criteria that are based on the user requirements determined by the project sponsor. Each of the criteria is weighted by a scale factor ranging from values of 1 to 3. The scale factor scores the importance of each criterion based on its impact on the project. A scale factor of 1 has minimal impact on the project, while a scale factor of 3 is crucial to the outcome of the project. The current soft material 3D printer produced by graduate student James Lorenz will serve as a baseline to compare with the team's design concepts. James Lorenz's design solutions for his pump, mixing system, and extruder will receive a score of zero across all of the criteria.

Finally, each team member rated the four design concepts for each printer subfunction with a score of -1, 0, or +1 across each criterion. A score of -1 means that the design will perform worse towards completing the requirement compared to James Lorenz's design while a score of +1 means that the design outperforms the baseline. Then a score of zero means that the design will have minimal impact on the requirement. To determine how the design concepts will compare to James Lorenz's current solution, the team researched the effectiveness of similar designs, discussed with stakeholders, and performed simple qualitative and quantitative comparative analyses. After each team member filled out the Pugh Charts individually, the team discussed their scores and then agreed on a final ranking for each design concept.

Table 6. Pugh chart for the pump/feeder design concepts.

Pump/Feeder Design Concepts						
Requirements/ Criteria	**Scale Factor (1-3)**	**Lorenz Current Solution**	**Electric Pump**	**Motor Syringes**	**Gravity Fed**	**Archimedes Screw**
Reliability and Repetition	3	0	-1	+1	-1	0
Printer Dimensions	1	0	0	0	-1	0
Print Dimensions	2	0	0	0	+1	+1
Minimize Gas Content	3	0	0	0	-1	0
Wide Range of Functional Gradients	2	0	0	+1	0	+1
Design is organized and aesthetically pleasing	1	0	0	+1	0	+1
Total		0	-3	6	-5	5

After undergoing the concept selection process for the optimal pump/feeder system using the Pugh Chart in Table 6, it was determined that the Motor Syringe system had the highest rating with a total score of 6. James Lorenz uses a progressive cavity pump for his current design. His pumping system is used as a baseline to compare with the team's design concepts. The progressive cavity pumps are precise, consistent, and reliable at pumping a wide variety of fluids, but they are not great for repeatability due to their expensive cost. For the first criterion of "reliability and repeatability", we determined only the motor syringe pump out-performed James Lorenz's model with a score of +1. The motor pump features a reliable and precise transmission system, along with its low cost and high level of customizability, which contribute to its high repeatability factor. Next, the “printer dimensions” refer to whether the pump/feeder system fits within the required printer specifications. All the pumps require a similar feeder size that meets printer dimensions, therefore they received a baseline score of 0. The only exception is the gravity-fed pump which will likely require a larger tank since there is no additional force pushing the fluid downward. The print dimensions correspond to how much fluid can fit into each pump. The cavity pump, electric pump, and motor pump have a fixed feeder size so received a rating of 0 while the gravity-fed and Archimedes screw allows continuous addition of fluid during printing so got a score of +1. All of the pump designs have insignificant effects on the “minimizing gas content” requirement, except for the gravity-fed method which does not have a constant flow and therefore may allow air bubbles into the mixing system so receives a score of -1. The rating for the “wide range of functional gradients” requirement is directly proportional to if the feeder system can incorporate multiple materials and is easily tunable. The motor syringes and Archimedes screw both meet this requirement to receive a score of +1. All other requirements were not affected by the motor system and received a score of 0. Lastly, the team reviewed that the motor syringe pump/feeder design is truly the optimal system by confirming it is capable of passing all the user requirements and can easily be fabricated and implemented into the team’s design.

Table 7. Pugh chart for the mixing systems design concepts.

Mixing System Design Concepts					
Requirements/ Criteria	**Weight Factor (1-3)**	**Lorenz Current Solution (Impeller Static Mixer)**	**Dynamic Mixer**	**Tank Baffles**	**Magnetic Spinner**
Reliability and Repetition	3	0	+1	+1	+1
Material Premixing	3	0	-1	-1	-1
Printer Dimensions	1	0	0	-1	-1
Minimize Gas Content	3	0	-1	0	-1
Wide Range of Functional Gradients	2	0	-1	-1	-1
Total		0	-5	-3	-6

As shown in the Pugh Chart in Table 7, the optimal mixing system was found to be James Lorenz's Impeller Static Mixer. The baseline score of zero for the impeller static mixer is higher than the total score for the other mixing systems. James Lorenz studied how this mixer can efficiently mix Silicone and its curing agent in his original soft material 3D printer. Though this impeller static mixer is efficient, it is less repeatable than the other dynamic mixer, tank baffle and magnetic spinner since silicone can easily cure within the mixer, necessitating frequent replacement. Therefore, the three design concept mixers received a rating of +1 for the reliability and repeatability requirements. Compared to the Impeller static mixer, it can be concluded that the dynamic mixer, tank baffles and magnetic spinner systems will perform worse on mixing the material due to the possibility that material can flow through the mixing system before passing through the blade. In addition, the impeller static mixer is the only design that ensures multiple gradient ranges can be mixed together. Therefore the three design concepts received a score of -1 for the "material premixing" and "wide range of functional gradients" requirements. In addition, the tank baffles and magnetic spinner are much larger than the baseline model so received a score of -1 for printer dimensions. Also, the dynamics mixer and magnetic spinner received a score of -1 for minimizing gas content due to the possibility of bubbles being introduced from the spinning process which is unlikely in the baseline static mixer. Finally, the team reviewed and added up the scores and confirmed the impeller static mixer would best meet all the user requirements.

Table 8. Pugh chart for the extruder design concepts.

Extruder Design Concepts					
Requirements/ Criteria	**Weight Factor (1-3)**	**Lorenz Current Solution (Tapered Nozzle)**	**UV Curing**	**Variable Diameter**	**Syringe**
Reliability and Repetition	3	0	-1	-1	0
Material Premixing	3	0	0	0	-1
Printer Dimensions	1	0	0	+1	+1
Minimize Gas Content	3	0	0	-1	-1
Print features ≤ 0.5 mm	2	0	+1	+1	+1
Total		0	-1	0	-3

After undergoing the concept selection process for the optimal extruder design as seen in the Pugh Chart in Table 8 above, both the Tapered Nozzle and the Variable Diameter concepts had a total score of 0. However, because minimizing gas content is a driving requirement, and the Variable Diameter nozzle has the potential to introduce air into the solution, the Tapered Nozzle was determined to be the best concept for the extruder.

Thus, after going through the entire concept generation and selection process, the concepts chosen for the Alpha Design of the 3D printer are the motor syringe for the pumping system, the impeller static mixer for the mixing system, and the tapered nozzle for the extruder. Figure 14 portrays initial sketches for these concepts:

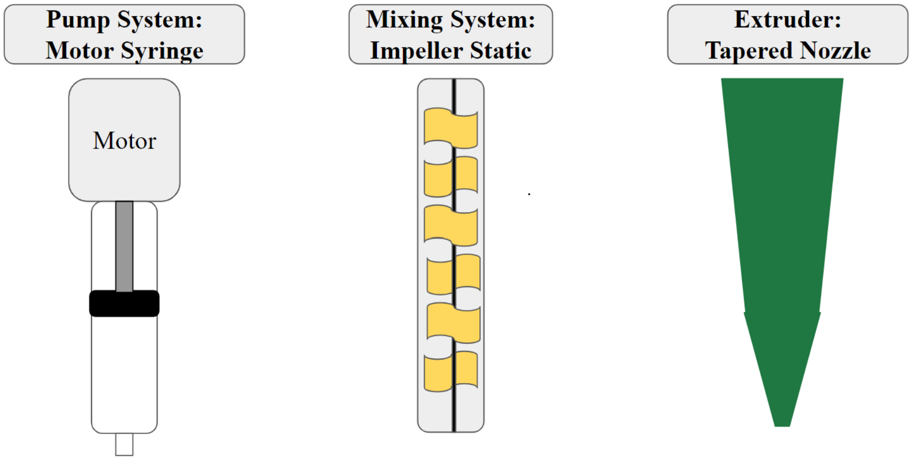


Figure 14. Winning Design Concept for the pump system, mixing system and extruder

THE “ALPHA DESIGN”

After the divergent and convergent design thought processes of the concept generation and selection phase, the preliminary printer design utilizes motor syringes, an impeller static mixer, and a tapered nozzle. This combination of subsystems will allow for precise volumetric output while ensuring the silicone is properly mixed and dispensed in the appropriate location.

Once motor syringes were determined to be the best option, a preliminary design was developed after considering the necessary system requirements (Figure 14). It was determined that four syringes would need to be utilized as two dual-part silicone kits [41] would be mixed together to produce the desired mechanical properties in the dispensed silicone. As each component in the individual dual-part silicone kits needs to be mixed in equal volumes to cure, only one motor is needed for each silicone kit. As specified in Table 2 previously, the maximum print size was determined to be a 25x25x40mm rectangular prism. This requires a total volume of 25,000 cubic millimeters or 25 CC. As this device should be able to print uniform samples as well, the minimum capacity of each syringe is 12.5 CC. With this in mind and user desire to potentially print multiple samples at once, syringes with a 30 CC capacity were utilized in the preliminary design. Furthermore, to reduce complexity and increase ease of maintenance, *NEMA17 1.8° Stepper Motors* were selected for use to match the existing stepper motors of the *Prusa MK3S+*[4].

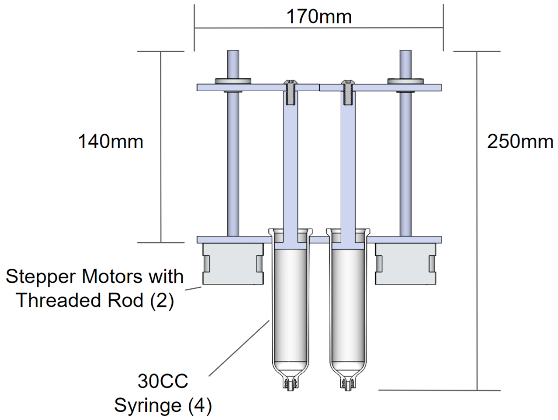


Figure 15a. Cross-sectional view of motor syringe subsystem

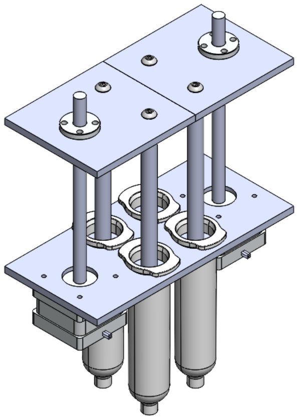


Figure 15b. Isometric view of motor syringe subsystem

After the silicone components are output from the motor syringes, they will be fed into the impeller static mixer. As this is the same mixer utilized in James Lorenz's printer, the team was able to consult him regarding mixer usage and problems that were experienced. In Lorenz's experience, a mixer that had at least seven helical elements sufficiently mixed the silicone components, thus an impeller static mixer with eight helical elements was selected for use. Additionally, there was an issue regarding the leftover silicone curing inside of the mixer. To solve this, Lorenz uses an SLA Resin 3D printer to manufacture disposable mixers that are easily replaceable. At this time, the team will follow this example and utilize disposable impeller static mixers. For the extrusion nozzle, this will utilize a standard syringe Luer Lock connection to attach to the end of the mixer (Figure 15). To improve the ease of maintenance, the team will utilize standard disposable tapered syringe nozzles that can be easily swapped out if it is damaged, clogged, or needs to be cleaned. To determine the appropriate nozzle diameter, further research and empirical testing is required.

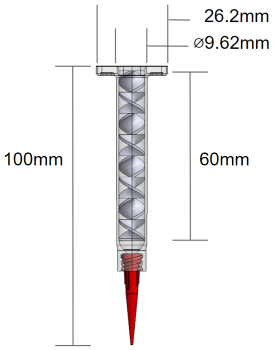


Figure 16a. Cross-sectional view of mixer and nozzle

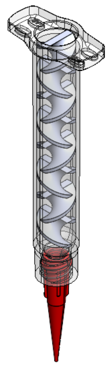


Figure 16b. Isometric view of mixer and nozzle

Combining these selected subsystem designs with the *Prusa MK3S+* frame, the team was able to develop a completed preliminary design for the printer (Figure 16). This design mounts the motor syringes to an additional frame above the extrusion mechanism. This frame is only a preliminary design and will be modified by the team as deemed necessary. Due to the motor syringes being mounted vertically and above the extruder, gravity will be acting in the direction of flow, assisting the components in moving through the system. Additionally, having the motor syringes not rigidly mounted to the mixer, allows for the extrusion nozzle to move as needed during print operations. Instead, the motor syringes will output into flexible tubing connected to the mixer. Utilizing the existing extrusion mechanism carriage of the *Prusa MK3S+*, the mixer with the extrusion nozzle will be mounted onto the carriage to allow for utilization of the existing positioning system. While this preliminary design exceeds the size specified by the user requirements, future revisions will be made to the device frame to reduce overall size.

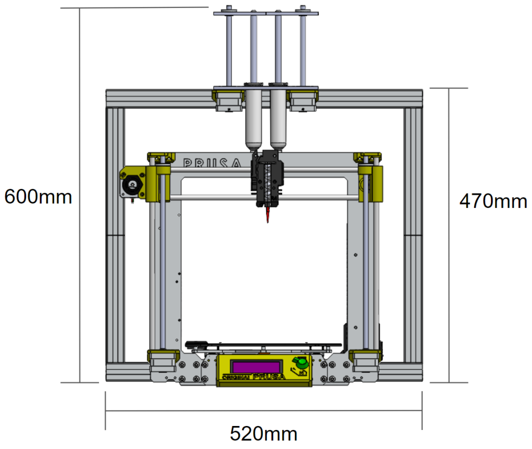


Figure 17a. Front view of preliminary printer design.

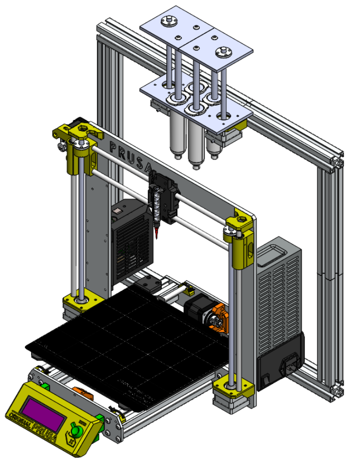


Figure 17b. Isometric view of preliminary printer design.

PROBLEM ANALYSIS AND ITERATION

The user requirements and specifications for this project demand complicated engineering fundamentals to be considered in order to successfully go through the design process, and then assess whether the final solution meets the quantified engineering specifications. Figure 18 shows the four main general areas to be reviewed for this project (p. 34):

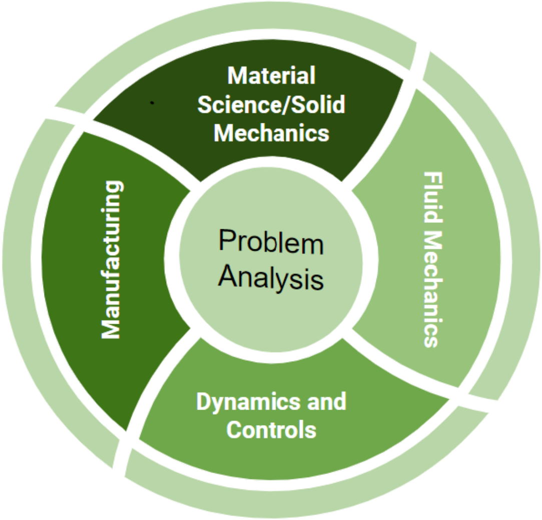


Figure 18. Four main engineering areas to consider for specifications analysis.

The project specifications revolve around the four main engineering fundamentals shown in Figure 18.

Materials science is the engineering fundamental that is critical to the output of the 3D printer. Requirements 1B and 2B from Table 3, which involve the gas content within the print and functional gradients, will require this fundamental for evaluation. An anticipated challenge for the output is being able to reliably measure both the gas content and the gradients within the final print, and complex material science principles will have to be applied. In order to address this challenge, there have been consultations with John Estrada and his research group, who have been working on evaluating these materials. A task has also been delegated to research methods of testing material gradients.

Fluid mechanics, inversely, is most critical to the input of the device. Modeling the behavior of the silicone as it is mixed and being able to control the flow rate of the extrusion is essential for 3D printing with these materials. Requirements 2A and 3B, involve material premixing and gradient range. The values for these requirements are expected to be adapted slightly as empirical testing is performed on the materials themselves. They are heavily related to the silicones used in the final design, as well as the mixing process being used. A related challenge we expect to arise involves the mixing of the silicone resin. These materials are highly viscous fluids and often don’t mix easily. This can affect the curing consistency of the silicone and will cause imperfections in the gradient [16]. In preparation, research has been conducted on mixing methods of similar materials, and testing has been planned to evaluate different mixing methods.

Dynamics and controls are related to most of the moving parts of a 3D printer. Requirements 1A and 4B involve reliability and precision, which will depend heavily on the precision of the controls. On top of controls relating to the movement of the extrusion head, they will also need to be developed in order to properly control the concentration of silicone that is being extruded from the pumps. The material composition will have to be varied continuously, and the material composition and behavior will make this especially difficult [11]. To combat this, the development of possible control systems has been made a priority early on and will be adapted as prototypes are developed. Additionally, a meeting has been scheduled with James Lorenz, who is experienced in developing control systems for 3D printers and working with G-code, which is a language used to translate machine motions. Finally, manufacturing is tied in with the project as a whole, as 3D printing and silicone mixing and curing are both manufacturing processes.

With the Alpha Design, some engineering analysis and calculations have been made in order to assess the selected concepts with respect to the engineering requirements and specifications. A very important part of this project is actuators and transmissions. In order to start working on a physical prototype of the 3D printer as soon as possible, the team has to make decisions regarding the possible motors and transmission systems required for the pumping system. Thus, motor and transmission system analysis and calculations have to be performed. These calculations will be useful to meet volume output and printer resolution requirements since the pumping system is closely related to both of these features.

The volumetric flow rate of the device is controlled by the motor syringes and is critical knowledge for determining the printer resolution and print speeds. This directly relates to the user requirements and specifications for the variable mixing ratios and high print resolution. By having precise control of the motor syringes, the volumetric flow rate can be precisely controlled, allowing for high-resolution printing and for the print speeds to be tuned accordingly. In order to analyze this, a formula must relate the stepper motor resolution to the volumetric displacement of each syringe.

$$\left(\frac{Stepper\ Motor\ Resolution\ [degrees/step]}{360\ degrees}\right) \times Threaded\ Rod\ Pitch\ [mm] = Vert.\ Disp.\ [mm/step] \tag{3}$$

$$(\pi \times (Syringe\ Inner\ Radius\ [mm])^2) \times Vert.\ Disp.\ [mm/step] = Vol.\ Disp.\ [mm^3/step] \tag{4}$$

By utilizing Eq. 3 and 4 above, the volumetric displacement of the syringes may be determined and related to the stepper motor resolution. With the current components of the preliminary design, the stepper motor resolution is 1.8° per step [4], the threaded rod pitch is 1 mm, and the syringe inner radius is 11.285 mm [42]. Inputting these parameters, the volumetric displacement of each syringe is found to be approximately 2.00 mm^3 per step.

Due to the results of the calculations relating the stepper motor resolution to the volumetric output of the extruder, further analysis is required to determine a transmission system that would reduce the amount of material expelled per step of the motor. This transmission system will be utilized to meet the 0.5 mm resolution engineering requirement discussed and shown in Table 3. Due to their compactness, transmission ratio flexibility, and high power-to-weight ratio, gears were chosen for the transmission system [43]. To simplify the calculations, the volume output from the extruder was assumed to be a rectangular prism, with length and width of equal dimensions to that of the nozzle diameter. The volumetric output, in mm^3, of the extruder can be calculated with Eq. 5:

$$Output = \frac{d^2 \cdot 0.5}{4} \tag{5}$$

where d is the nozzle diameter, and 0.5 represents the print layer height, based on the 0.5 mm resolution requirement. The squared diameter and height factor are divided by four because the alpha design involves one syringe per silicone component, and thus the desired volumetric output of each would be a quarter of the total output.

As mentioned above, without a transmission system, each motor step will output 2 mm^3 of material per syringe from the extruder, so the minimum gear ratio required to get the desired resolution is given by the quotient of the un-modified system, and the output with transmission involved, as shown by Eq. 6:

$$Gear\ Ratio = \frac{2.4}{Output} \tag{6}$$

where output is the previously calculated volume extrusion with Eq. 5.

Based on stakeholder input, the available nozzle diameters with the tapered nozzle chosen for the Alpha Design [42] lead to a range of possible tapered nozzle diameters of 0.25 mm - 0.60 mm. Using Eq. 5 and 6, Table 9 shows the possible gear ratios required for this project:

Table 9. Volumetric output and subsequent gear ratio are required for each nozzle diameter. Gear ratios are rounded up to the nearest whole number, to fulfill the minimum ratio requirement.

Nozzle Diameter	Volumetric Output (mm^3)	Gear Ratio
0.25	0.0078125	1024
0.33	0.0136125	588
0.41	0.0210125	381
0.51	0.0325125	246
0.60	0.045	178

After discussing these results with the primary stakeholders of this project, the decision to not include a transmission in the build design was made. This was due to the gear ratios being much higher than expected; thus, it would increase complexity and cost while greatly reducing speed. With this, further engineering analysis was required to determine alternative solutions to increase the resolution of the extrusion system.

Up to this point, the design of the control system for the printer was not a focus. As a *Prusa i3 MK3S+* [4] is the base of this project, the basic firmware and controls for the printer are open-source and easily accessible. After further research into the system controls, it was discovered that the default firmware had a solution to increase the resolution and precision of the motor movements. This solution is microstepping. Microstepping is a common method to increase the maximum resolution of stepper motors by breaking each motor step into many microsteps. While microstepping does come with reduced holding torque and some positioning error, it is an intriguing solution that would be of great benefit to the project [4]. The *NEMA17 1.8° Stepper Motors* have a microstep resolution of up to 256 microsteps per step [4]. If fully implemented, this resolution can negate the need for a transmission for nozzle diameters above 0.51 mm (Table 9). With this, a nozzle diameter of 0.51 mm was selected for use in the build design to accompany the 256 microstep resolution. Further verification will be required to determine if the system is capable of maintaining a 256 microstep resolution while extruding. If it is found to not be feasible, the microstep resolution may be reduced and then accompanied by a smaller transmission in future design iterations.

Using *SOLIDWORKS* Flow Simulation, models of the mixer subsystem, and the material properties of the silicone components, Finite Volume Analysis was conducted on the internal flow of the mixer. The silicone components used in the simulation were *Smooth-On*'s Ecoflex 00-10 and Ecoflex 00-50 [41]. These silicones are utilized by the ESMech Lab and have a high enough variation in material properties to make them suitable for this analysis.

To conduct the simulation, the desired volumetric flow rate out of the mixer must be established. From Table 9, the theoretical volumetric output of each syringe per step is noted as 0.0325125 mm^3 for a 0.51 mm diameter nozzle. Referencing the specification for requirement 4B from Table 3, the printing speeds of the printer must be between 15 to 25 mm/s. Assuming that one step is equivalent to moving the distance of one nozzle diameter, this leads to an approximate speed of 30 to 50 steps/s. Combining this with the volumetric output per step of four syringes, the volumetric flow rate out of the mixer will be approximately 3.9 to 6.5 mm^3/s. For the simulations, a constant volumetric flow rate of 5.2 mm^3/s out of the mixer was maintained. To analyze varying mixing ratios, the flow rates of each component were modified to the appropriate ratio in order to maintain the 5.2 mm^3/s flow rate out of the mixer.

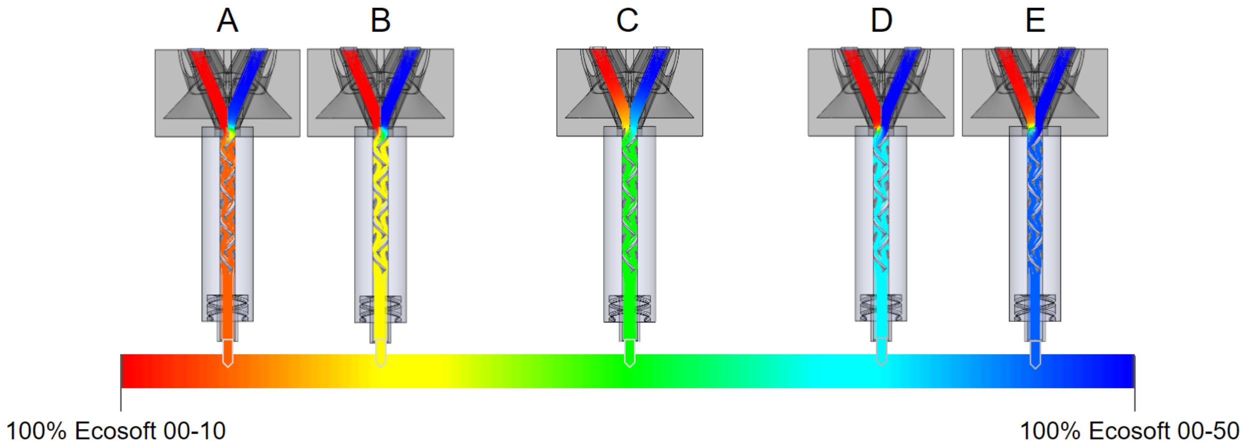


Figure 19. Visualization of *Solidworks* flow simulation results for the mixing of silicone components in an impeller static mixer. The mixture color shifting from red to blue indicates a decrease in Ecosoft 00-10 concentration and an increase in Ecosoft 00-50 concentration. The volumetric flow rate ratios for A, B, C, D, and E were 9:1, 3:1, 1:1, 1:3, and 1:9 respectively.

As shown above in Figure 19, by varying the flow rates of each component, various mixing ratios may be achieved. Each simulation result indicated a mixture quality within 0.005% of the target value. This indicates that the mixer subsystem is theoretically capable of producing a gradient of material properties through precise control of the volumetric flow rates. From these results, the specifications for requirements 1A, 2A, and 3B (Table 2 and 3) are theoretically satisfied and the mixer subsystem may be implemented into the build design. With this, it is important to note that the simulations do not account for changing the volumetric flow rates during operation and only represent mixing at a constant ratio. Further verification will be conducted empirically to determine if theoretical simulations match empirical results and if varying the volumetric flow rates during operation results in a gradient as expected.

BUILD DESIGN

With the initial theoretical and computational engineering analysis done, a new iteration of the design could be produced. The alpha design served as a base for the build design, with the first addition to it being the intended transmission. With the gear ratio calculations described before, the team started sourcing a set of gears to design and build a compound gear train with a gear ratio of 16:1. Research and browsing showed that for such a high gear ratio, and with the printer's size constraints, gear options were very limited. The gears that worked were either completely out of budget for the project or would need a very long gear train that would not fit within the project's size constraints. Due to lack of time, the team approached the project's sponsor to look into "forgetting" about the transmission and focusing on this printer's main objective: gradients. With the sponsor's approval, the team decided to eliminate the transmission system from the design, which would limit the printer's resolution, but would allow the project to move forward with achieving gradient properties during printing.

With that decision, the team could produce a second iteration of the overall design. All subsystems followed the same basic engineering design from the Alpha Design, with complimentary components added only. Figure 20 shows a digital embodiment of the pumping/feeding subsystem:

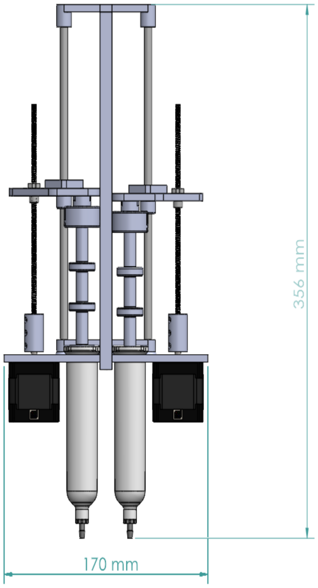


Figure 20a. Front view of pumping subsystem.

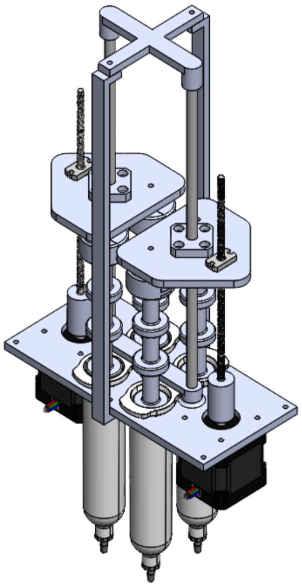


Figure 20b. Isometric view of pumping subsystem.

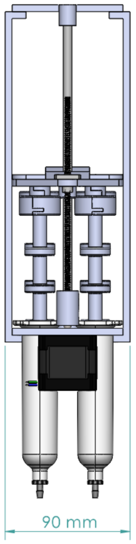


Figure 20c. Side view of pumping subsystem

Each stepper motor is directly connected to its respective threaded rod by an in-house coupler. Guide rods are rigidly connected to the main platform and structural pieces at the top and bottom. A linear bearing is used to reduce friction for each guide rod. Syringe plungers are secured to their respective moving plate and syringe. Not seen in Figure 19, tubing will be used to connect each syringe to the mixer, using luer-lock-to-barbed adapters. Figure 21 shows the mixer/extruder design:

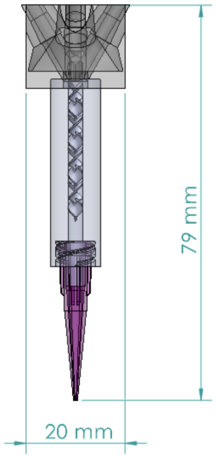


Figure 21a. Side view of mixer/extruder subsystem

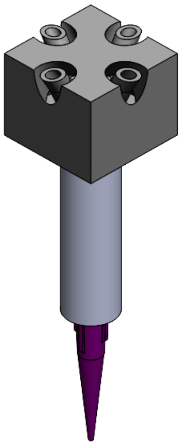


Figure 21b. Isometric view of mixer/extruder subsystem

An in-house manifold is used to connect the mixer to each syringe. This manifold leads all silicone components to the inside of the mixer. The impeller static mixer with eight helical elements is then connected to a simple tapered nozzle, with a luer-lock fitting. Figure 22 shows the overall digital assembly of the printer design:

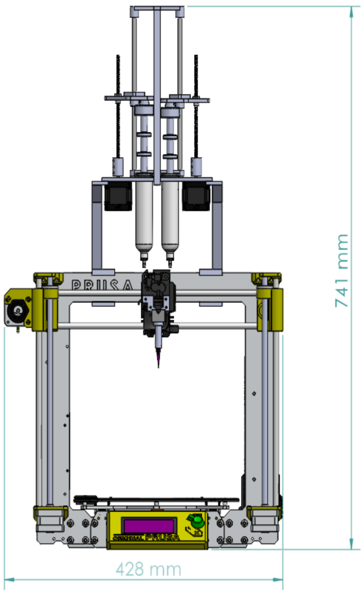


Figure 22a. Front view of overall printer assembly.

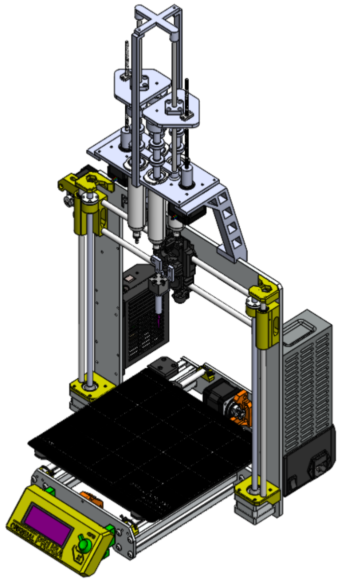


Figure 22b. Isometric view of overall printer assembly.

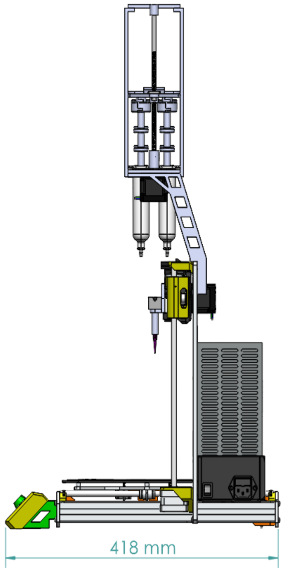


Figure 22c. Side view of overall printer assembly.

With the digital embodiment of the design ready, the team could start ordering all parts there were going to be outsourced and manufacturing all in-house components.

In-house parts were all 3D printed with either a resin-3D printed or a filament-3D printer. Thus, no manufacturing plans were necessary for any components used in the overall build design. Figure 22 shows pictures of the physical embodiment of the build design:

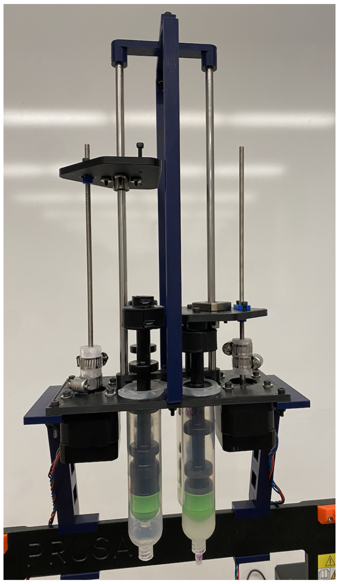


Figure 23a. Pumping/feeding subsystem of build design.

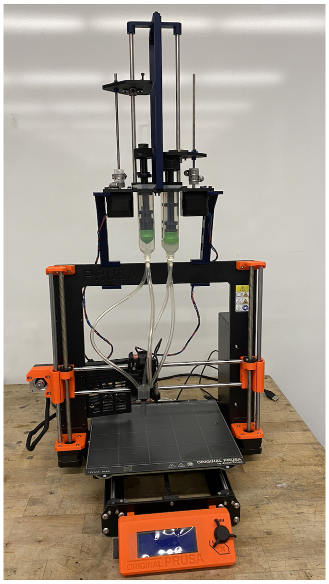


Figure 23b. Overall build design

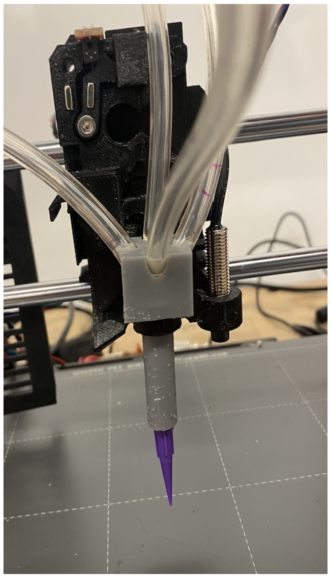


Figure 23c. Mixer and nozzle of build design.

VERIFICATION AND VALIDATION

After completing the assembly of the final design, the team will carry out verification and validation testing. The verification tests ensure that the assembly properly meets the engineering specifications, and the validation tests ensure that the sponsor's expectations are met. The verification tests will expand on the previous engineering analysis which verified that the subcomponents, such as the pumping system, mixer/extrusion system and electronics/controls, all functioned properly. Verification testing will be performed using a variety of methods such as empirical testing, visual testing, pre-setup measurements and modeling to ensure that each engineering specification is met. Verification plans/ designs of engineering (DOEs) are organized for each of the specifications (See Appendix B). The team is currently undergoing verification testing. Verification tests are complete for requirements 3A, 4A and 3B, in progress for requirements 2A, 1B and 2B and not yet started for requirement 1A. Table 12 below summarizes the verification testing plans and current progress for each of the seven engineering specifications.

Table 12: List of the verification plans and progress for each of the corresponding engineering requirements and specifications.

Requirement	Specification	Verification Testing Plan	Testing Progress
1A. Reliability and Repetition	Hardness Coefficient of Variation ≤ 10%	Empirical Test: Use a durometer to measure hardness values of printed silicones. Compare for 3 samples of each silicone type.	Not Started
2A. Material Premixing	Relative Mixing Index ≥ 0.7	Empirical Test: Use MATLAB code to compare the color of the individual silicone parts to the final mixed part for each silicone type.	In Progress
3A. Printer Dimensions	Frame dimensions ≤ 500 mm x 500 mm x 450 mm	Pre-setup Measurement: Measure both the CAD model and build dimensions with a ruler.	Complete
4A. Print Dimensions	Print dimensions ≤ 40 mm x 25 mm x 25 mm	Pre-setup Measurement: Calculate volume of total syringe output with given measurements.	Complete
1B. Minimize Introduction of Bubbles	Bubbles introduced during mixing have a diameter ≤ 175 μm	Visual Test: Visually verify that no bubbles are present in prints of each silicone type.	In Progress
2B. Two Degrees of Freedom	Printing path is controllable in X and Y directions as concentrations vary	Visual/Modeling Test: Create controls to print 2D gradients and visualize color gradient change for both directions.	In Progress
3B. Variable Mixing Ratios	Mixing ratio can be intentionally changed by ≤ 10% during printing	Empirical Test: Confirm that the syringe provides accurate output by comparing the input control value to resulting output measurement.	Complete

The verification for requirement 1A confirms the printer's reliability and repeatability by using empirical tests that compare the material properties between printed silicone samples. The verification tests must meet the specification that the hardness of the silicone samples have a coefficient of variation of less than 10%. The hardness of the silicone prints will be measured using a durometer, which gives a hardness value from 0 to 100. The team decided to use a "Shore durometer A test" since it is used to measure flexible rubbers such as silicone. Tests will be carried out for three samples of each of the three types of silicone. Verification tests for this requirement have not yet begun, but the team has organized a detailed procedure to carry the tests out in the coming weeks. The procedure ensures that experimental trials consist of each silicone sample. An equal 50/50 output of the silicone part A and part B will be mixed by measuring 5 mL for each of the Silicone parts before they are outputted into the syringe. In addition, the mixed silicone will be outputted into equal sized molds to ensure the shape of the printed material measured by the durometer is equal across all samples. The hardness value will be taken for each of the samples and inputted in Table 13 below. Then, the mean, and standard deviation, of each of the silicone materials will be calculated. Lastly, the coefficient of variation will be calculated using Equation 7 below. Verification for requirement 1A will be deemed successful if this equation gives a value of less than 10%.

Table 13. Data table for the verification tests for requirement 1A. Hardness values for each silicone sample is calculated using a durometer.

Silicone Type	**Hardness Trial 1**	**Hardness Trial 2**	**Hardness Trial 3**	**Average**	**Standard Deviation**
EcoFlex 00-10	##	##	##	##	##
EcoFlex 00-50	##	##	##	##	##
Dragon Skin 20	##	##	##	##	##

$$Coefficient\ of\ Verification = \frac{\sigma}{\mu} * 100 \tag{7}$$

The error for the unitless coefficient of verification value is found to be the resolution error of 0.5 from the duromer as well as the accuracy error from 3 sample trials.

Requirement 2A looks to verify the ability of the system to properly mix the silicone parts by meeting the specification of having a relative mixing index of greater than 0.7. This specification is verified using empirical testing consisting of coloring the silicone parts and running them through the mixing. The coloring of the original parts will be compared with the finished mixed color using MATLAB code. The experiment, as outlined in Appendix B, ensures consistent results for each trial by following procedures such as pouring equal parts of each silicone component, mixing in equal amounts of coloring dye and taking pictures with the same lighting conditions and camera configuration. The pictures of the premixed and mixed silicone will be uploaded to the team's original MATLAB code (found in Appendix B). The code compares the final solution to separate components (neutral control), and side-by-side components (actual mixing comparison) and results in a mixing index value from 0 to 1. A value of 0.7 is needed to pass our specification. This procedure is repeated with multiple trials with different color dyes to ensure reliable results. In addition, the procedure is repeated for each silicone type. Images testing the mixing of EcoFlex 00-50 parts can be seen in Figure 24 below.

Figure 24a. Syringes used to measure equal parts of EcoFlex 00-50 Part A (yellow) and Part B (blue).

Figure 24b. Inputting silicone into the syringe system. This setup ensures there is proper back pressure to help with extrusion and prevent dripping.

Figure 24c. Verification test 2A. The two silicone parts of EcoFlex 00-50 are extruded with equal volume and flow rates. The materials are mixed to form a green color as seen at the end of the nozzle

Preliminary testing for requirement 2A was currently done only once, because of time constraints. Pictures of the two, unmixed components and of the mixed silicone were taken and modified for analysis. The modification consisted of simple image cropping, so nothing but the actual silicone components would be analyzed by the MATLAB program. The unmodified images can be found in Appendix B. Figure 25 shows the modified images used for analysis:

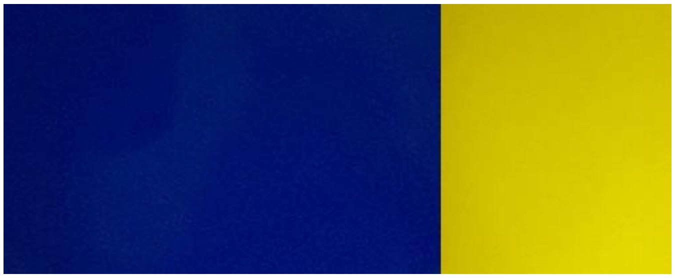


Figure 25a. Unmixed silicone components for EcoFlex 00-50 Part A (yellow) and Part B (blue).

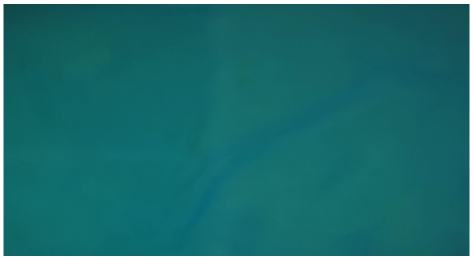


Figure 25b. Mixed silicone for EcoFlex 00-50 Part A and B.

With these images, the MATLAB program was used to compare the standard deviation of pixel intensity of the two, unmixed silicone components, to the standard deviation of pixel intensity of the mixed silicone solution, with the RMI. This test yielded an RMI of 0.915, which is above the 0.7 requirement. Because this test was performed only once, the only source of error for this value is the resolution of the camera, but because this resolution error is so small compared to the RMI value - about 1x10^5 times smaller - it is negligible. One result is not statistically significant, so this test will need to be repeated multiple times to completely verify that the mixer design actually meets the user specification. Nonetheless, this first test might be a good indication for it.

Requirement 3A is simply verified by using measurements of the printer dimensions to confirm it meets the volume stated in the engineering specification. The necessary length, width and height measurements are both measured using the CAD modeling of the printer assembly as well as using a ruler to measure our completed build. This verification test was completed, although the measurements of the height were determined to not pass the specification requirement. The specification of the printer height was written to be 450mm, but the measured value was found to be 741± 0.5 mm. This was addressed with our sponsor, and he stated that it is acceptable for our height to be at this value due to this being a low priority specification. The length and width dimensions were found to fit within our specifications with values of 428±0.5 mm and 418±0.5 mm. The error was determined to be from the resolution of the ruler.

Similarly, the print dimension requirement, 4B, can be verified by using simple measurements. The maximum print dimensions can be determined based on the amount of silicone that can be extruded by the printer. Therefore, this is found by the total volume that the four syringes can hold. From the manufacturer of the syringes, they are said to hold a volume of 45 mL. This gives a total possible silicone volume and therefore print dimension of 180 mL which is much larger than the specification volume of 40mm x 25mm x 25mm or 25 mL. No error is reported due to no information given from the manufacturer's product details.

Requirement 1B is another driving requirement for the 3D printer. From interviews with the project sponsor and stakeholders, we’ve found that bubbles that are large enough to confirm visually can cause problems when testing the materials. Having fully printed 3d materials has fallen out of the scope of this project, however plans to account for bubbles include visual inspection of 3d printed samples when completed, along with image processing of materials. Several samples will be produced and different people will visually inspect them for trapped air. Secondly, matlab image processing will be run on the samples with controlled lighting in order to test for trapped air. Should it be found that the amount of air trapped causes the specification to be failed, troubleshooting will be performed to isolate places where air could be introduced to the system, and postprocessing, such as placing printed samples in a vacuum to reduce air will be looked into.

Requirement 2B is that the printer must be able to perform with two degrees of freedom. This specification doesn’t require testing, as it is more a physical requirement for the printer itself. The design that has been implemented currently allows for three degrees of freedom, so this requirement has been met.

Requirement 3B is that the printer must be able to print with variable mixing ratios. To validate this requirement, several tests were performed on the extrusion system to measure that the imputed steps of the system result in a predicted output of silicone at varying levels. The syringe was loaded from the bottom using an adaptor in order to minimize air in the cylinder. The syringes were then mounted to the motor and plunger for extrusion. Tubing was attached to the end of the syringes, and an initial value was measured. From there, the motors were run at varying steps, and the distance traveled down the tube was measured. Pictures of the experimental setup can be seen in Figure 25b below. Error was derived from resolution of the calipers used for measuring and precision found through multiple tests. The results of this testing can be seen in Figure 26 below.

Figure 26a. Picture of experimental setup used to measure output of motor-syringe system

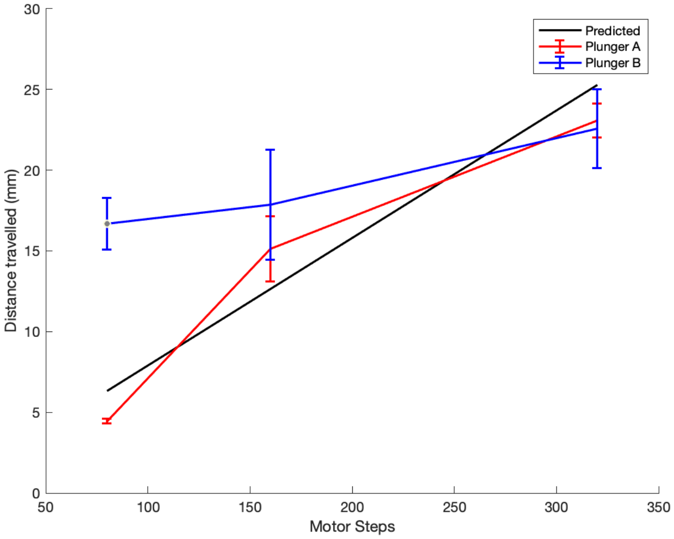


Figure 26b. Predicted and experimental distance traveled down the tube vs input motor steps.

As can be seen in Figure 26b, several problems have been encountered. The distance traveled down the tube is not very close to the predicted values, especially for the smaller steps, and the error is quite high. This could be due to several factors, such as the positioning of the motor causing a moment on the bearing. This would cause the bearing to stick and prevent the extruded amount to meet the predicted value. Secondly, the error is very high which is a result of inconsistency in the data. The testing procedure definitely lacked some of the equipment required for testing of an adequate number of data points, and the use of calipers to measure the distance traveled proved to be an unreliable method. Future testing will utilize a precision scale in order to measure mass output of the syringes, which should be more accurate. Additionally, testing on the final prototype will have enough tubing and testing equipment to measure more data points and help reduce outliers. Finally, the output between the two syringes should be matching since they are both moved by the same motor. The variation is likely due to a lack of rigidity in the 3d printed parts, along with the aforementioned moment on the bearing. The final design and verification method will attempt to mitigate these issues and meet the specification.

VALIDATION

The validation for this project will be done through user testing, performed by Professor Estrada and the ESMe Lab. Because of the time constraints of ME 450, the ESMe Lab will have to finish building and optimizing the printer - mainly adding the transmission system and completing controls - and then start with the validation protocols. Figure 27 summarizes what areas will user testing focus on:

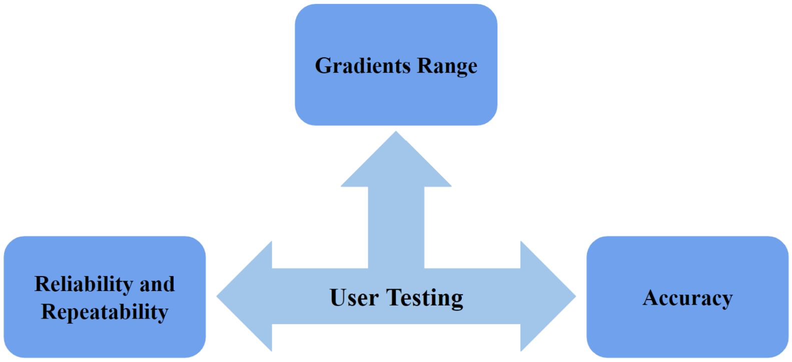


Figure 27. Validation areas for user testing

For reliability and repetition, Professor Estrada and his lab will have to see if the final design is reliable enough for their research. This will involve constant printing and testing of products, using the experimental techniques required to establish the standards the ESMe lab aims to institute. To check for reliability, multiple samples with the same geometry and intended material properties will be produced and tested. The difference between this user testing validation, and user requirement 1A, is that the project requirement is based on industry standards for manufacturing processes in general, while this validation protocol will test the reliability of the printer design with respect to the needs and objectives of Professor Estrada and his lab.

A very important part of the printer's validation is to check if the range of possible material property gradients is large enough for the research done at the ESMe lab. Establishing material characterization protocols is a very important and complicated matter, and so a wide range of gradients will be needed to have all-encompassing standards for functionally gradient soft materials. Thus, the user testing for this part of the validation process will consist of going through all possible gradients, after installing the transmission and finishing the controller, to see if the research objectives of the lab can be fulfilled with the current printer design.

The accuracy of the printer, specifically accuracy of material properties will also be evaluated. The reliability and repetition validation protocol will test the printer's precision, but the accuracy is also very important. The degree of accuracy with which the printer can produce material gradients has to be good enough for the ESMe lab research. Thus, Professor Estrada and his lab will have to test samples with different intended material properties to check that they actually show those characteristics. This validation could be done in conjunction with the reliability and repetition validation protocol, since the testing methods will be the same - material properties tests done at the ESMe lab - and can show results for both precision and accuracy.

DISCUSSION

With additional time and resources, the team would be able to explore methods to take our design from a functional prototype to a reliable final product for use in both research and industry application. The team could elaborate on the problem definition by going beyond our initial goal in utilizing the device for material validation and instead apply the device in real-world applications such as in 3D printing complex and customizable biomedical devices. This would require the team to ask questions about the 3D printed part complexity, precision and dimension requirements for such devices. There are three categories that the team can look into for expanding the problem statement to use the device for industry applications; creating a more repeatable printing process, printing complex shapes and enhancing the material validation protocol.

Currently, the printing process of the device is not easily repeatable due to requiring replacement parts after each trial and requiring a complicated process of inputting the silicone into the syringe system. In the team's current printing methods, we must replace the mixer, nozzle, tubes and syringes during each printing trial. This is due to the silicones curing in the mixer/tubes once the printing process is complete. It is a cumbersome and wasteful process to have to replace all these parts. With more time, the team could research better methods of cleaning the printer without having to replace the parts for each trial. This could potentially include using a silicone solvent to dissolve the excess material or including pressurized air to push the material out of the system. In addition, the team could look into a more efficient process of inputting the silicone into the syringes. The team could perform validation methods into different methods of inputting the silicone that reduces setup time, allows larger volumes, and prevents back pressure.

Additionally, further improvements into the printer controls are needed to be studied to scale-up the printer applications. There is a time delay when running the control system from when the motor turns on to push the piston down in the syringe system to when material is actually pushed through the tubes and extruded from the nozzle. The time of this delay must be studied through empirical tests of running multiple trials of the printer with various silicone types. This time delay is important to precisely compute because it determines when the gantry system controls must begin running to start the print. Moving the gantry system too early/late from when the silicone outputs from the nozzle will cause deformities in the shape.

For the current problem definition, the printer only needs to be able to output gradients in two dimensions in order to characterize material properties, but for real-world applications it is necessary to be able to print complex three dimensional shapes. In order to enable more complex material structures to be produced and analyzed, the final design will implement gradient printing in three dimensions. This will enable gradients to not only be produced on the XY coordinate plane, but also vertically along the z-axis. With more time, the team can create controls that allow printing 3D gradients. For complex shapes, the team could research into the ability of controlling the printer to create strong silicone supports that can hold the structure together, or even plastic filament supports using the previous Prusa printer's filament extruding system.

Lastly, to ensure that the prints meet the high-standards of the biomedical industry, the device must be able to work with high accuracy and precision as determined by a standardized protocol to verify the mechanical behavior of the printed materials. With more time, the team could use the current design of the printer to perform a series of empirical tests to characterize various material properties. These tests could include a durometer test to measure material hardness, a tensile test to understand stress concentrations in gradient soft materials or a strain-rate test to quantify a material's toughness. It would be important to note variations in quantities between print sample trials to determine the precision error. Following such material validation tests will let the team conclude if the output prints can meet the standards needed across certain industries.

The team can reflect back after completing the final build and testing of the innovative 3D printer to highlight the true strengths/weaknesses of the design. The team has identified the three main strengths of the design to be the material mixing from the mixing subsystem, the pumping of silicone in the syringe-motor subsystem, and creating an overall cost-effective and accessible printer. The first strength, proper material mixing, was proven during the successful verification testing for a proper mixing index for requirement 2A. The team successfully incorporated the impeller static mixer design as inspired by James Lorenz, to work with the gantry system given by the Prusa printer frame. The team iterated on the static mixer design to function with four inputs (Two types of Silicone Part A and B) that are simultaneously introduced into the mixer. Though it was a challenge to control the silicone in the tubes to reach the top of the mixer at the same time, once the silicones reached the mixer, it proved successful in evenly mixing the material during each of our trials. Having a mixed silicone material properly extruded from the nozzle was a big milestone in the functionality of the printer.

The design of the syringe-motor pumping system was the most innovative and time-consuming aspect of the project design, but proved to be one of the biggest strengths of the project. The concept of pumping material out of syringes with a motor system was completely novel for this application in a 3D printer. The concept selection process of a pumping system was quite a challenge due to the wide variety of paths the team could take, but ultimately the syringe-motor systems seems to play out as the best option. The dual motors system was strategically built to guarantee that there was an even ratio output of each Silicone Part A and B while still allowing the variable mixing ratio needed to make a gradient as stated in requirement 4B. The team successfully wired the stepper motors into the Prusa electronics assembly and modified the controls coding to allow the pumping system to be meticulously controlled. This precise control over the output of the two silicone's while allowing an even mixing of the curing parts helped fulfill the team's primary objective of printing gradients with the extruded soft materials.

Lastly, the team successfully was able to build the printer using readily-available and low cost materials. The current commercially-available methods of printing soft materials are expensive, so this project aims to create a cost-effective 3D printer with the goal of making FGSM research more accessible to researchers. All the parts used in this project were either made in-house using 3D printed parts or from low-cost manufactures. The cost-effective design of this printer was a true strength to this project as it highlights the novelty of the team's design and larger impacts for advancing research with FGSM.

The team has identified three main possible weaknesses of the final design: the structural robustness, silicone components curing inside the printer components, and silicone back flow from the mixer. The first weakness is with the strength of structure, which faces difficulties due to the vibrations, torques and pressures in the system. Specifically, vibration has been seen to be an issue during tests due to continuous running of both stepper motors, at different speeds. These vibrations could lead to undesirable mixing ratios, inaccurate geometric features, and overall long-term damage to the printer components. To combat this problem, the team iterated on the design of the syringe-motor system so that the motor and syringed flipped positions in order to reduce motor torque. The team also plans to build the syringe base plates out of a metal material using water jetting rather than the current 3D printed base. The current plastic base plates begin to deform due to the torque from the guide rod. A more robust design would allow the system to be more repeatable for long term use.

An additional weakness in the final design is that the silicone cures inside the printer components, such as the flexible tubing and the mixer. The curing components of the two-part silicones used as feedstock start to cure as soon as they leave the bottle. Because of the slow printing speeds, there is a chance for the curing component to start curing inside the flexible tubing, which would block the way for new feedstock and completely ruin the gradients and overall printing. Additionally, if for some reason printing has to be stopped, the four-component silicone inside the mixer could start curing, and block the pathway for overall printing. To tackle this problem, the team will have to characterize curing as much as possible, and tune up the pumping and extrusion of silicone so nothing cures inside the device. This will come mainly from empirical data, due to the variability of curing times depending on the mixing ratios being commanded to the printer.

The last weakness of the design is from the silicone back flow which is another possible significant problem that the team has to consider. Resistance caused by the mixer can lead to a pressure-induced opposite to the intended direction of travel. If this pressure is larger than either of the controlled pressures provided by the motors, it could potentially result in backflow. This issue is shown in Figure 28:

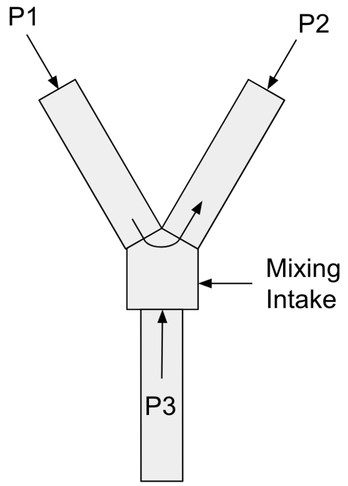


Figure 28. Illustration of potential issues with backflow being introduced to the system. P1 and P2 represent the silicone pressures generated from the motor, P3 represents back pressure from the mixer

As can be seen in Figure 28, if the resistance pressure, P3, from the mixer is greater than either of the silicone pressures, P1 and P2, it can lead to one of the silicone components to flow up the tube of the other. Anticipating this, empirical and theoretical fluid analysis will be conducted in order to model the magnitude of this back pressure. Additionally, motors will be selected that will allow sufficient force to overcome these pressures.
The team experienced many challenges in the design process that required several design iterations before the final build. These challenges included the novelty and limited prior research with this work, the time and budget constraints for the team as well as the many technical design weaknesses that were discussed previously.

One particular technical challenge was that the Silicone materials have a high viscosity, making it a fluid dynamics challenge to smoothly extrude and control the flow during the printing process. This property of silicone is what makes the current available silicone printers so expensive due to requiring precise control systems. To minimize these risks, the team looked to create an extrusion system that reduces internal friction and contains adequate pressure control. For example, the tubing connecting the syringe pumping system to the mixer extruding systems was shown to contain a lot of friction while the silicone traveled through it. To overcome this challenge the group reiterated on the design to minimize the tubing length. Although it may be viscous, the silicone is still a liquid which poses another challenge in controlling its flow. For example, any trapped air in the syringe would cause a back pressure that would cause unwanted dripping of the silicone into the tubing. This backpressure was minimized through a trial and error process of finding the best way to implement the silicone material into the syringe without allowing any air in the system. The team found the best way to solve this problem was by actually inputting the silicone from one syringe using another syringe.

Potential risks that may be associated with the end-user of this design stems from working with the moving parts and pressurized system of this 3D printer. The user must follow any precautions for using a typical 3D printer such as keeping away from any moving parts when the printer is running to prevent mechanical hazards. In addition, this printer relies on using the pressure from the motor causing the pistons to push the silicone down in the syringes. This can be a potential danger in case there is a rupture in the system that could cause materials to explode out. Proper care should be taken to ensure that the system is safe before running the printer and building up this pressure.

FINAL DESIGN

The final design for the 3D printer is largely similar to the build design in many key areas. Most of the issues experienced during testing were related to the pumping subsystem. This was the main focus for the final design, as our mixer was able to meet our requirements. Figure 29 seen below shows the changes made to this subsystem.

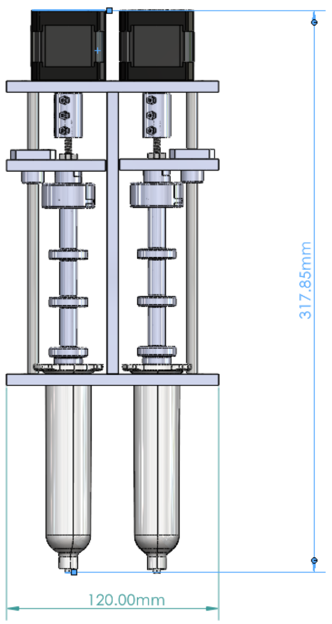


Figure 29a. Front view of pumping subsystem.

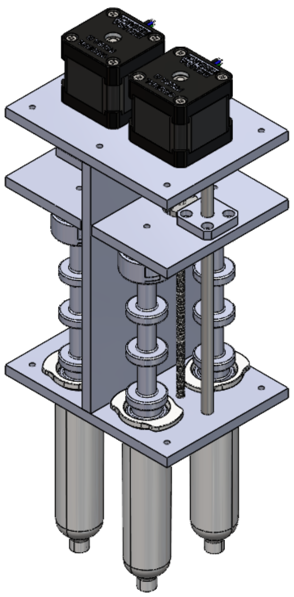


Figure 29b. Isometric view of pumping subsystem.

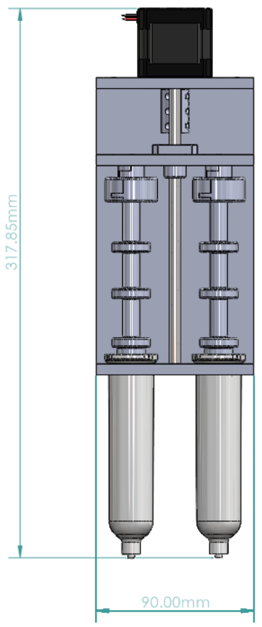


Figure 29c. Side view of pumping subsystem

For the pumping system shown above, the main differences between the build and final design are in the structure and component orientation. During testing, it was observed that the offset position of the motor and lead screw were causing a significant moment around the guide rod bearing, leading to inconsistency in our extrusion results. The pressures required to push the silicone resins through the mixing subsystem ended up being higher than anticipated, which is likely the cause of the moment. The original reason for the offset in design was a lack of space on the base plate, as the motor and syringes would interfere with each other. The final design aims to mitigate this problem by inverting the motors. By placing the lead screw in the center between the two syringes, the moment arm is negligible, and the pressure from the plungers should work against one another. An added benefit is that the design changes allow the width to be reduced by 50 mm, however the height is increased.

Another key design change is the structure of the final design. In the build design it was observed that the plates were bending and twisting, and many aspects of the structure lacked sufficient rigidity. These issues would greatly impact performance, and cause our control inputs to have widely varying results. To account for this, the final design incorporates more solid connections, most notably the large center plate. The guide rods and lead screws feature more stable connections to the top and bottom plates to reduce any change in orientation caused by the high pressures in the syringes. To account for the twisting motion, tighter tolerances were implemented.

The bending of the plates and structural components was due to the material properties of the PLA used during fabrication of the build design. The decision to use 3D printed components was made to accommodate the need for rapid prototyping imposed by the tight timeline, along with weight concerns. For the final design, metal would be implemented for all of the structural components and plates. Many of these components were designed with this in mind, and are intended to be waterjet from ¼ in. aluminum stock. This would greatly reduce the amount of bending in the plates and help to minimize the resulting issues experienced during verification.

REFLECTION

The resulting design from this project has potential to help the world in many ways. The research done by professor Estrada and his team at the ESMEch Lab could lead to a widespread use of functionally gradient soft materials in the engineering world. Establishing the material characterization standards for these kinds of materials will enable the biomedical industry to produce synthetic bone-tendon connections, or help patients that require vocal folds reconstruction. Even though the 3D printer developed during this project will not directly make these products, it will assist in the journey necessary for manufacturers to confidently and safely release these inventions. Public health, safety, and welfare are very relevant in the context of this project. The standards that the ESMech Lab will establish will enable the safe production of biomedical products, as stated before. Patient health and welfare will be able to be addressed safely with a successful printer design and production.

The design developed during this project has the potential to have an impact in the global marketplace too, if done correctly. As seen on the stakeholder map shown in page 9, the ESMech Lab is not the only stakeholder for this project that could use the printer design for their own objectives. If allowed by Professor Estrada, the printer's design could be shared or sold to other material science labs around the world to advance the research into functionally gradient soft materials even more. Thanks to the flexibility of manufacturing that comes with 3D printing, different laboratories could use the printer to satisfy their specific needs when it comes to test samples. The printer is cost-effective and simple enough for researchers from all over the world, no matter how many resources they have backing their work, to employ it in their laboratories.

Apart from the impacts on the biomedical industry discussed before, the main social impacts associated with this printer design come from regular use and disposal. To make the printer easier to use, some components were designed to be disposable, specifically the flexible tubing, the syringes, the mixer, and the tapered nozzle. This decreased the amount of parts needed to be designed in-house, the amount of maintenance required for the printer, and the overall cost of manufacturing and use. However, more plastic and resin will need to be consumed with disposable components. This in itself represents a social impact alone, because of environmental pollution related to plastic and resin production [45][46]. On top of that, the disposal of these plastic and resin products also leads to environmental pollution in landfills, or emissions from waste incineration, if not done responsibly [46]. Overall, the design developed during this project has the potential to have very little social impacts associated with manufacture, use, and/or disposal of parts, as long as components are sourced from responsible sources, and plastic and resin parts disposal is done in a way to minimize pollution. Not a lot of tools were used to characterize the potential societal impacts of the design, since those impacts are very simple to understand, and resource consumption for the printer is still somewhat unknown. The main way of gauging how big will the use and disposal impacts be was to talk with Professor Estrada about his plans for the printer. Nonetheless, research at the ESMech Lab is still in its early stages, so there is no real estimate on how big or small the social impacts discussed be. For the same reason, life cycle assessment tools can not be used to produce numbers for these impacts, since the inputs necessary for these kinds of programs are still unknown.

This printer design does not have a lot of potential economic impacts associated with manufacture, use, and/or disposal. Because the printer is projected to be a one of one prototype, at least for the near future, the manufacturing did not have any major impacts in the economical sense. For its use, silicone, plastic tubing, and resin will need to be purchased constantly, depending on how much the printer is used, so providers for these materials will have almost constant business. Lastly, the disposal of waste components will require responsible practices, as mentioned above, so there will be some minor economic impact on organizations that are dedicated to plastic and resin recycling or disposal.

All team members have very similar cultural backgrounds, privilege, and identities. Even though one team member is an international student, he has been in the United States long enough to adapt to American work and academic culture. All team members have done all their engineering training at the University of Michigan, so work styles and approaches were very similar. Throughout the semester, all team members were on the same page about how to approach each stage in the design process, and how to tackle the "logistical" portions (meaning the reports and presentations) of the project too. Even though how similar all members of the team were did have its benefits, it also brought some problems, especially in the concept generation stage. Most concepts proposed by different team members were the same or very similar to other members' ideas. Thus, the concept generation stage started out somewhat limited in that sense, and the team had to work a little harder to overcome its similarities. The project sponsor also has a very similar background and style to the team, which made the relationship between team members and sponsor very easy to establish. The power difference with the sponsor never led to any trouble throughout the project. Sponsor needs were very clear since the beginning of the project, which made the design process very simple in terms of knowing what would, and what wouldn't, satisfy sponsor needs.

For this project, the primary stakeholders are end users themselves. This allowed for the complexity of the power dynamics to be simplified, but still allowed for differing perspectives to provide feedback. While the stakeholders themselves have a strong background in academic research and experimental design for research devices, the project team had limited experience prior to this project. All of the members of the project team have similar technical backgrounds, so by consulting the stakeholders, a more diverse collection of viewpoints was able to be utilized when designing the device. In order to balance these viewpoints, the project team met weekly with the primary stakeholders to discuss design decisions and established focus areas for each team member. These focus areas began as the subsystems of the device and then expanded as project needs and complexity increased. The ideas for each focus area primarily came from the respective team member associated with that specific area. These ideas would be discussed within the team and the stakeholders, but due to time constraints, some ideas were unable to be iterated upon as much as they needed to be. As a whole, this resulted in an imbalance in perspectives for some design aspects, but balanced out as the project proceeded.

In general, any cultural differences that existed between team members had little impact on the approach that the team took throughout the project. The differences that influenced the team's approach to the project were focused on utilizing team member's strengths to improve efficiency and ideally the end product. As far as cultural similarities, all of the team members have similar academic backgrounds and thus similar ideas regarding how to approach the project. While still academic based, the project sponsor focuses specifically on academic research. Due to this, the project sponsor would identify key focus areas to guide the team through the design process and design iterations in order for the final design to better fit the user requirements. This resulted in a more refined final product that would better fit the needs of the end users.

When designing the project, ethical dilemmas were centered around the cost, accessibility, and use cases for the device. The cost and accessibility of the device are partially tied together. As found in the background research for this project, similar devices cost over $24,000 [16]. These devices also tend to have proprietary software that has limited modification options. This project was able to produce an experimental device for less than ten percent of the cost of similar devices and utilized open-source firmware which is available to anyone who is interested. By keeping the cost of the device lower and using open-source firmware, this greatly increases the accessibility of the device. Regarding the use cases for the device, while primarily focused on academic research, the device itself is not configured to only operate for research purposes. When fully configured and refined, the device will operate as any typical 3D printer would. This allows for it to be used in academic research, manufacturing operations, or even hobbyist use. If the project was to enter the marketplace, these dilemmas may arise to some further issues. It may be found that the range of materials that the device can use does not quite encompass the needs of each user. This may lead to partial exclusion of a consumer group and thus not align with the project goals. Furthermore, as it is a device to manufacture products, some individuals may attempt to use the device to produce products with unethical intentions and context. This is not something that can be directly controlled, but will need to be kept in mind if this device was to enter the marketplace.

The personal ethics of the project team and the professional ethics that the University of Michigan expects to be upheld align well. The mission of the University of Michigan references applying knowledge and creating to enrich the future in order to better serve the people of Michigan and the world [19]. This project developed an experimental device that may be used to promote a fundamental advancement in the research of material mechanics. Ideally, this device will continue to be revised until it can be fully utilized, lead to global accessibility of affordable alternative medical solutions, and enable further enrichment of the future through advanced material research and development. Enrichment of the future may align with the ethics of future employers, however, employers will also aim to profit off of designs. As most employers need to make profit off of their products, this is inevitable. However, the team may continue to design in such a way to reduce manufacturing and development costs of the device, thus potentially reducing overall market cost.

RECOMMENDATIONS

The first recommendation for improving the printer is to redesign the motor syringe system mount. Currently, the whole system sits very high up, far away from the printing plate. This requires the flexible tubing connecting the silicone syringes to the mixer to be very long, which causes a considerable pressure drop from the pumping system, putting a higher strain on the stepper motors. Additionally, the long flexible tubing leads to a big delay between motor command to actual extrusion, which makes the system harder to model and its behavior harder to predict. Figure 30 shows the system mount that needs to be redesigned:

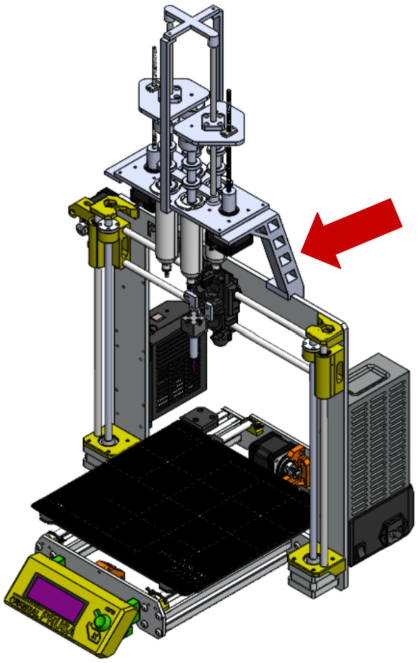


Figure 30. Motor syringe mount system to be redesigned.

As mentioned before, a transmission system will need to be implemented in the future. Currently, the printer resolution is lower than the 0.5 mm geometrical feature resolution originally stated as a requirement. This caused the team to remove the requirement for the time being, but it will need to come back throughout the future development of the project. A transmission system would not only improve the geometric resolution, but also aid with making smoother material gradients. Smaller, more controllable steps for the motors will mean better gradients, which are the main objective for this printer. Additionally, a transmission system will counteract the reduced torque resulting from motor microstepping, which would reduce the stress on the motors.

Another recommendation for the future is finding a better method for loading the syringes with silicone. With the current design, the best way as of now has been to push silicone into the syringes using smaller, disposable syringes, and adapters made out of luer lock-barbed fittings and flexible tubing. This has worked for initial testing, but it does come with problems. A significant amount of air is introduced into the system with this loading method, which goes against requirement 1B, *"Minimize Gas Content"*. More research into similar systems has to be done to see current solutions for this problem.

Initializing a cleaning procedure for the printer could help reduce consumption of disposable components and improve user experience. Oftentimes, components like the mixer or flexible tubing have to be replaced and disposed of even with just limited contact with silicone. This leads to a lot of waste of money and materials. Establishing a cleaning procedure for these kinds of situations could save a lot of time and resources. This could entail using silicone solvents, pressurized air, or water.

A very important part of the overall printer design is the mixer. To minimize the amount of air bubbles introduced during mixing, the team decided that the best manufacturing method for the mixers would be stereolithography (SLA) 3D printing. This kind of 3D printing uses resin as feedstock, which effectively seals the inside of the mixer from outside air. Even though this recommendation does not pertain to the printer design, it would be desirable for the ESMech Lab to acquire an SLA 3D printer of their own. This would not only be cost effective in the long term, because of the amount of mixers that will be used for testing during research, but also significantly reduce the turnaround time for possible design changes to the mixer.

The final design of the device uses six motors to perform any necessary extrusion or positioning steps. The stock *Prusa i3 MK3S+* uses five motors, with one for the x-axis, y-axis, and extruder, and two for the z-axis [X]. The stock model uses an Einsy Rambo control board that has four stepper motor controllers as it only has four control axes. Due to the implementation of a sixth motor for the second extrusion axis, a fifth motor controller was required as it would operate independently of all other axes. The current design solves this issue by wiring an external motor controller board to pins on the main board. In future iterations, it is recommended to change the control board to one that has at least five motor controllers already soldered onto it. This would reduce the need to identify pins to connect the external controller to, as well as reduce the necessary wiring modifications. Furthermore, this would eliminate excess wiring and electrical components, resulting in faster communications with the main control chip, and more precise control over the motor current.

The printer must maintain a high degree of precision and accuracy when in operation in order to produce samples that can be fully utilized in research. The control system must be fully validated and refined to ensure that every small movement occurs at the correct time, speed, and location. As the team was unable to complete the characterization of the system, it is recommended that further testing is conducted in order to establish time delays in the system, verify system resolution, and establish calibration curves for the positioning and extrusion motors. By determining the time delay in the system, delay may be implemented in the controller firmware to ensure all operations occur at the correct time. Establishing calibration curves for the motors themselves would allow for that curve to be looped back into the system to try and negate any error in positioning. This would further refine the precision and accuracy of the device, but would most likely be very time consuming due to the amount of trials that would be required. With this, these recommendations still are valid and would greatly improve the system as a whole.

CONCLUSIONS

This project aimed to help the ESMech Laboratory in their research on soft materials. Specifically, a reliable, cost-effective 3D printer was developed to provide a way of producing FGSMs to study. The intended use of this printer and its samples is to establish structured standards and procedures to verify the material properties of FGSMs. Current options for 3D printing FGSMs are very costly, making the research into these inaccessible for general academic institutions and laboratories. Success for this project could mean opening the door for a great number of people to get the implant or treatment they need, for a reasonable cost. Thus, the driving requirements for the 3D printer being developed were reliability and intended material properties accuracy. To tackle this design problem, the team first used flow charts and functional decomposition of the 3D printer. This resulted in three, main subcomponents of the printer that will need to be designed: the pumping system, the mixing system, and the extruder.

The team used concept down selection techniques like a literature review, stakeholder interviews, and pugh charts, to go from a vast group of concepts for each printer subsystem, to an alpha design. The concepts chosen were motor syringes, a static helical mixer, and a simple tapered nozzle. The general design worked with the use of two separate stepper motors, which are connected to threaded rods that push on syringe plunges to pump silicone at the desired rate. These syringes use flexible tubing to connect to the static helical mixer, which mixes the silicone feedstocks thoroughly before extruding the homogeneous mixture through the tapered nozzle.

An initial engineering analysis of the motors and transmissions required for this 3D printer, and both a Finite Volume Analysis and empirical testing of silicone mixing were performed to start studying how the alpha design would perform with respect to the engineering requirements of this project. Following this analysis, the team assembled the build design of the printer prototype that consisted of a combination of outsourced components as well as in-house 3D printed parts. The team also started with the verification process for the design, which showed promising results with respect to the user requirements established at the beginning of the project.

The overall design and physical prototype developed during the project is a very good step towards a final 3D printer for functionally gradient soft materials. The printer hardware and firmware is effective enough as a first iteration, but some design changes are required for improvement and optimization. The motors have to be repositioned to cancel couple moments with the back pressure coming from the syringes, mounting plates have to be manufactured out of metal to prevent bending, and a transmission system has to be implemented for better gradient and geometric printing resolution. The controls also have to be improved to implement 3D gradients, as opposed to only 2D. All these design improvements will be implemented by the project sponsor, Professor Estrada, and his team at the ESMech Lab.

ACKNOWLEDGMENTS

The team would like to thank Professor Jon Estrada and Joseph Beckett for their support and guidance throughout the entire semester. This project seemed to be extremely complicated, but with their help it turned out to be a very engaging challenge, instead of an impossible feat.

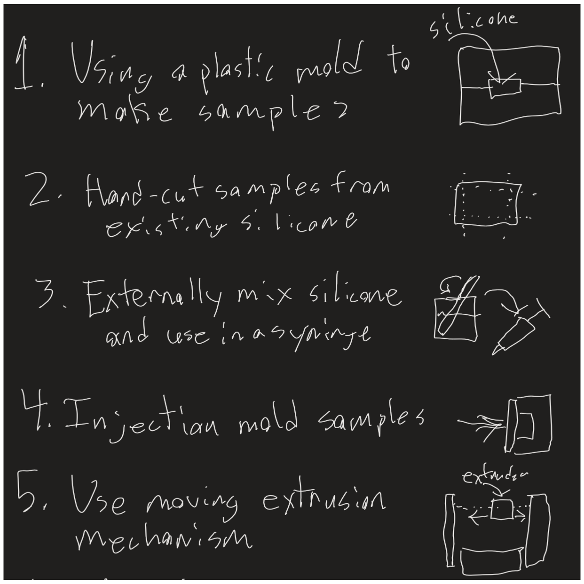
The team would also like to thank James Lorenz for his help with this project. James has been working with silicone printers for years, and his experience and guidance was vital for the project’s relative success. A lot of design decisions were influenced by his experience with these printers, and the final design would have not been able to get to this point without his help.

Finally, the team would like to thank Professor Kira Barton for her help throughout the semester. Professor Barton was instrumental in guiding the team throughout the design process and the class. No team member had been part of a design process from the ground up like in this class, so Professor Barton’s help was extremely useful.

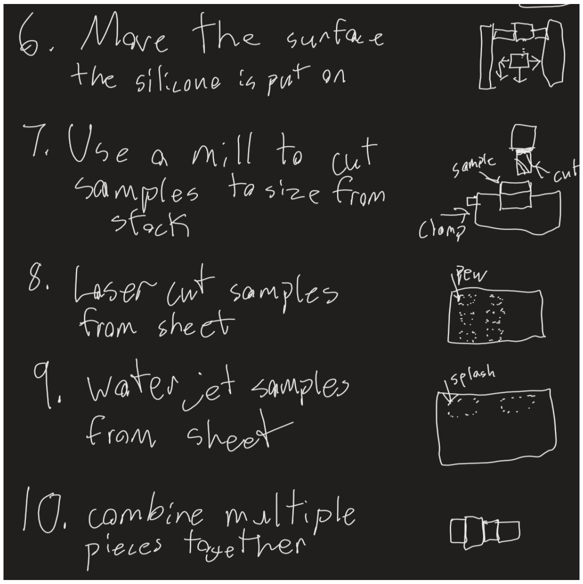
APPENDICES

Appendix A: Rapid Concept Generation Results

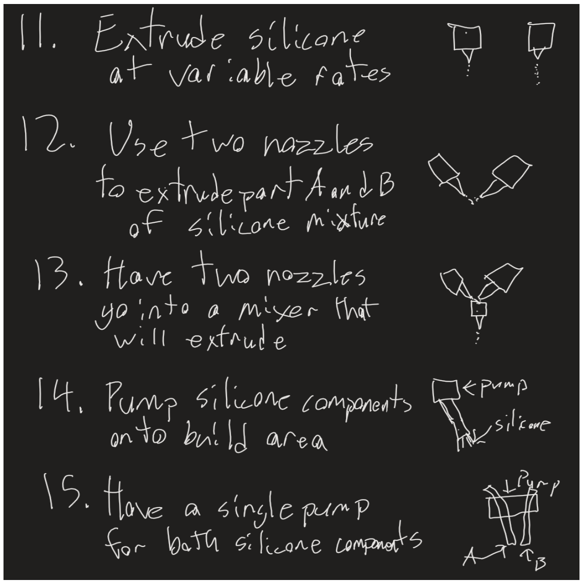
Evan Fassett - Rapid Concept Generation



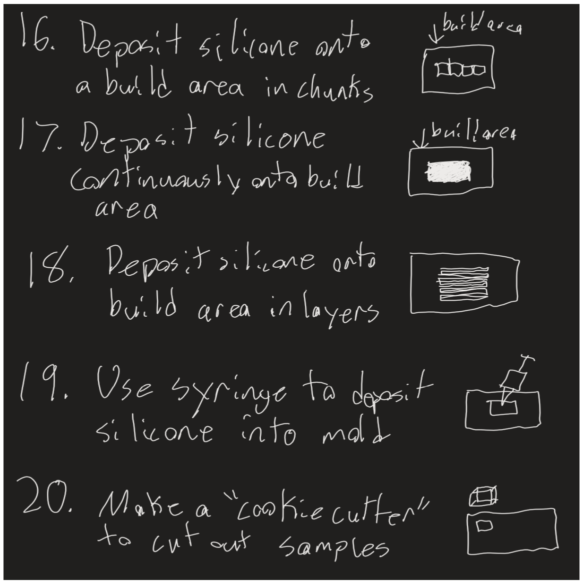
1. Using a plastic mold to make samples
2. Hand-cut samples from existing silicone
3. Externally mix silicone and use in a syringe
4. Injection mold samples
5. Use moving extrusion mechanism



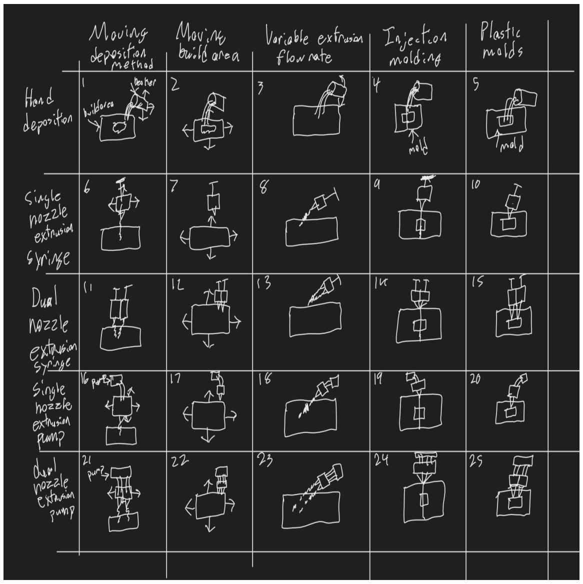
6. Move the surface the silicone is put on
7. Use a mill to cut samples to size from stock
8. Laser cut samples from sheet
9. water jet samples from sheet
10. combine multiple pieces together



11. Extrude silicone at variable rates
12. Use two nozzles to extrude part A and B of silicone mixture
13. Have two nozzles go into a mixer that will extrude
14. Pump silicone components onto build area
15. Have a single pump for both silicone components



16. Deposit silicone onto a build area in chunks
17. Deposit silicone continuously onto build area
18. Deposit silicone onto build area in layers
19. Use syringe to deposit silicone into mold
20. Make a "cookie cutter" to cut out samples

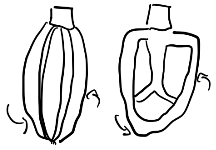


	Moving deposition method	Moving build area	Variable extrusion flow rate	Injection molding	Plastic molds
Hand deposition	1 beaker buildarea	2	3	4 mold	5 mold
Single nozzle extrusion syringe	6	7	8	9	10
Dual nozzle extrusion syringe	11	12	13	14	15
Single nozzle extrusion pump	16 pump	17	18	19	20
dual nozzle extrusion pump	21 pump	22	23	24	25

Adi Scharf - Rapid Concept Generation

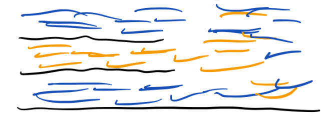
Mixing System Concepts

1. "Kitchen Aid" Mixer

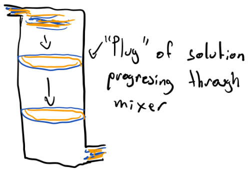


2. Jet mixer

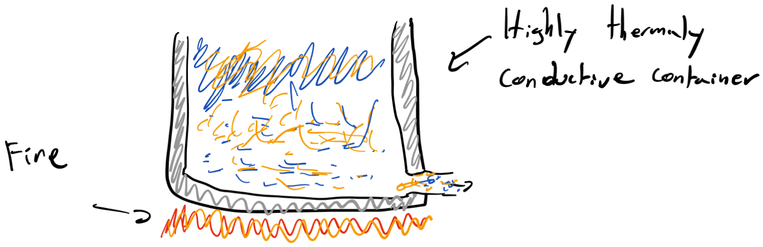
3. In pipe mixing



4. "Plug Flow" Mixing



5. Fire Mixer:

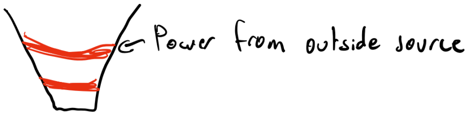


Extruder Systems

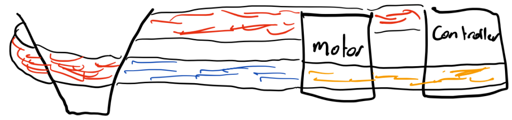
9. Syringe extruder

10. Variable diameter (Microscope like) nozzle:

11. Electrical heater extruder:



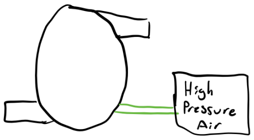
12. Heat pump extruder-printer



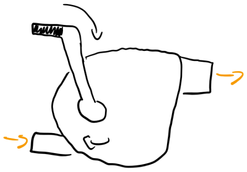
- Heating fluid in tubing cools down motor and controller, and "dumps" heat on nozzle

Pumping System Concepts

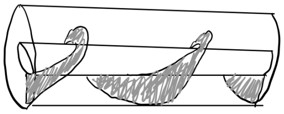
17. Air pump:



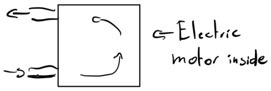
20. Manually cranked Pump:



19. Archimedes Screw

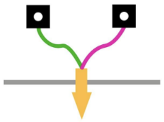


18. Electric Pump:



Charles Renz - Rapid Concept Generation

2. 20 Unique Concepts:
   1. Duel nozzle extrusion.

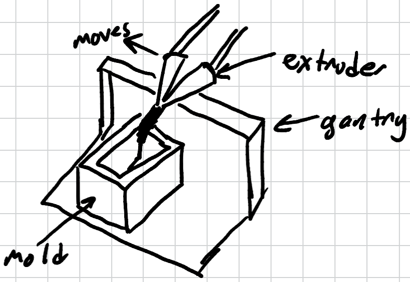


   2. Multi-material mixing: creates custom composites with given material ratios
   3. Thermal gradient control
   4. Variable hardness extruder
   5. Nozzle size adjustment
   6. Nozzle pressure adjustment - Pneumatic extrusion
   7. Flow rate adjustment – fluid dynamics control
   8. Varying extruder heads
   9. Use a magnetic lab stirrer in the mixing system
   10. Operate material mixing in a vacuum to limit air bubbles
   11. Utilize multiple interchangeable extruders in a rotating grid
   12. Apply UV light to induce material property change/curing
   13. Centrifuge material mixer
   14. Force based nozzle control
   15. Syringe adjustment nozzle control
   16. Use video feedback to project what 3D image looks like on surface
   17. Use a blender to mix materials before extrusion
   18. Extruder that can adjust material viscosity
   19. Extruder that can adjust material density.
   20. Apply chemicals to induce material property change/curing

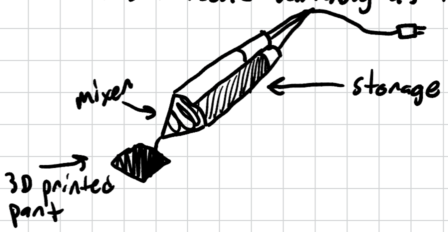
* attach more drawings below

Zachary Fuss - Rapid Concept Generation

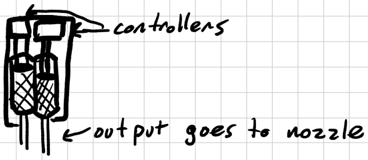
1.) Mold with automated dispenser. A pre-fabricated mold of the part in need with a nozzle that controls the concentration of silicone poured



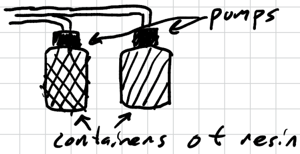
2.) Handheld 3d printing pen:
- design is drawn or traced by hand
- mixes silicone variably as more is extruded



7.) Pumping method: Controlled syringes
- controls the output of two syringes of varying concentrations of resin.
- Outputs this to mixer.

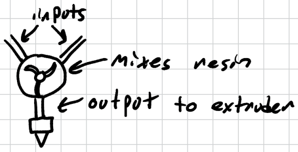


8.) Pumping method: Vats with attached pumps
- Two larger containers of pre-mixed resin

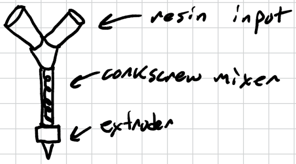


10.) Mixing method: small mixing cylinder => soft-serve style

- Inputs varying concentration of resin to mixer which outputs to the extruder. Flow rates kept constant

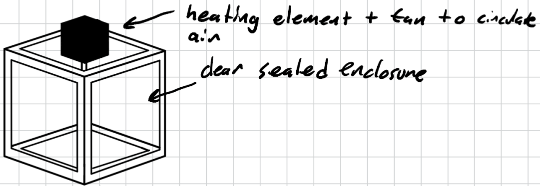


11.) Mixing process: Epoxy-style corkscrew, static
- Two inputs varying concentration of resin
- pumping method pushes resin through

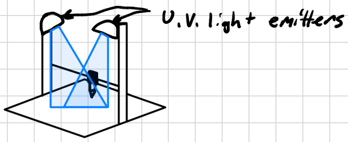


16.) Curing Speed: heated enclosure

- heated interior to encourage curing



17.) Constant U.V. exposure
- Emits a constant stream of U.V. light to encourage curing



Appendix B: Designs of Experiments

1A)

Requirement: Reliability and Repetition

Specification: Hardness and Local Geometry Coefficient of Variation ≤ 10%.

1. Run the pump, mixer and extrusion subsystem with a 50/50 silicone/cure for each of the 3 silicones. Output 5 mL for each of the two silicone/cure syringes. (Note max syringe volume is ~45mL).
    - The material is output into a 40mm diameter circle mold. (Therefore the height of each silicone trial should be ~8mm. The minimum height needed for the durometer test is 6 mm. 10000 mm = pi*(20mm)^2 * h. → h = 7.98 mm)
2. Wait for silicone to cure to their designated times.
3. Perform hardness testing using a durometer:
    - For hardness, use Shore durometer A test (shore A measures flexible rubbers that can range from very soft to hard). Each test gives a hardness value from 0 to 100. Durometer technical information:
4. Weigh the silicone samples. Use the density equation to calculate the volume of each sample.
5. Repeat for 3 trials of each material
6. Compare the hardness values and weights of each material to make sure they are within 10% of each other.

Hardness Test

Silicone	**Hardness Trial 1**	**Hardness Trial 2**	**Hardness Trial 3**	**Average**	**Precision Error**	**Resolution Error**
Eco flex 10						
Eco flex 50						
Dragon skin 20						

$$Coefficient\ of\ Verification\ =\ \frac{\sigma}{\mu} * 100$$

2A)

Requirement: Material Premixing

Specification: Relative Mixing Index > 0.7

1. Pour 5 mL of a silicone component and its corresponding cure component into separate containers (2 containers in total).
2. Put 2 drops of color on each component (2 different colors, one for each component), and mix thoroughly.
3. Take pictures with a tripod and ring-light of each one of the components separately.
4. Put silicone and its cure component side by side, without mixing.
5. Take pictures with a tripod and ring-light of the two-part silicone.

6. Put each component of the two-part silicone into their respective motor syringe, and prepare the system for running.
7. Run the pump, mixer and extrusion, and pour the resulting solution into a separate container.
8. Take a picture with a tripod and ring-light of the solution.
9. Upload all pictures to MATLAB code, and compare the final solution to separate components (neutral control), and side-by-side components (actual mixing comparison).
10. Repeat this procedure another time, with different colors (twice for each silicone type).

Silicone	Eco flex 10	Eco flex 50	Dragon skin 20
Eco flex 10			
Eco flex 50			
Dragon skin 20			

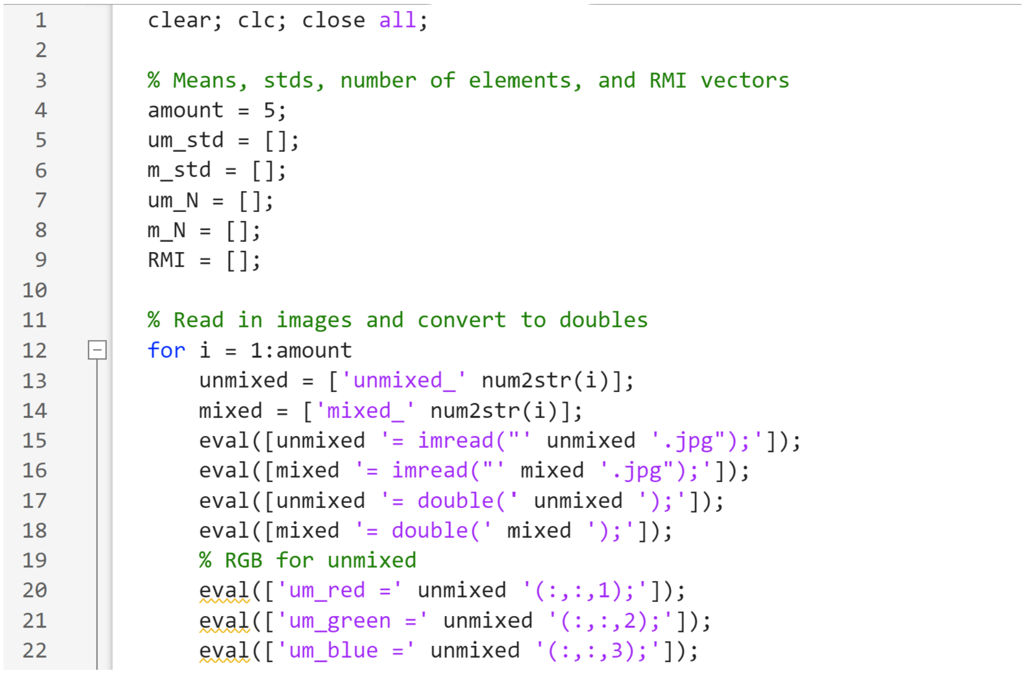
Unmodified images used for Imaging Analysis:

Unmixed component A

Mixed silicone solution

Unmixed component B

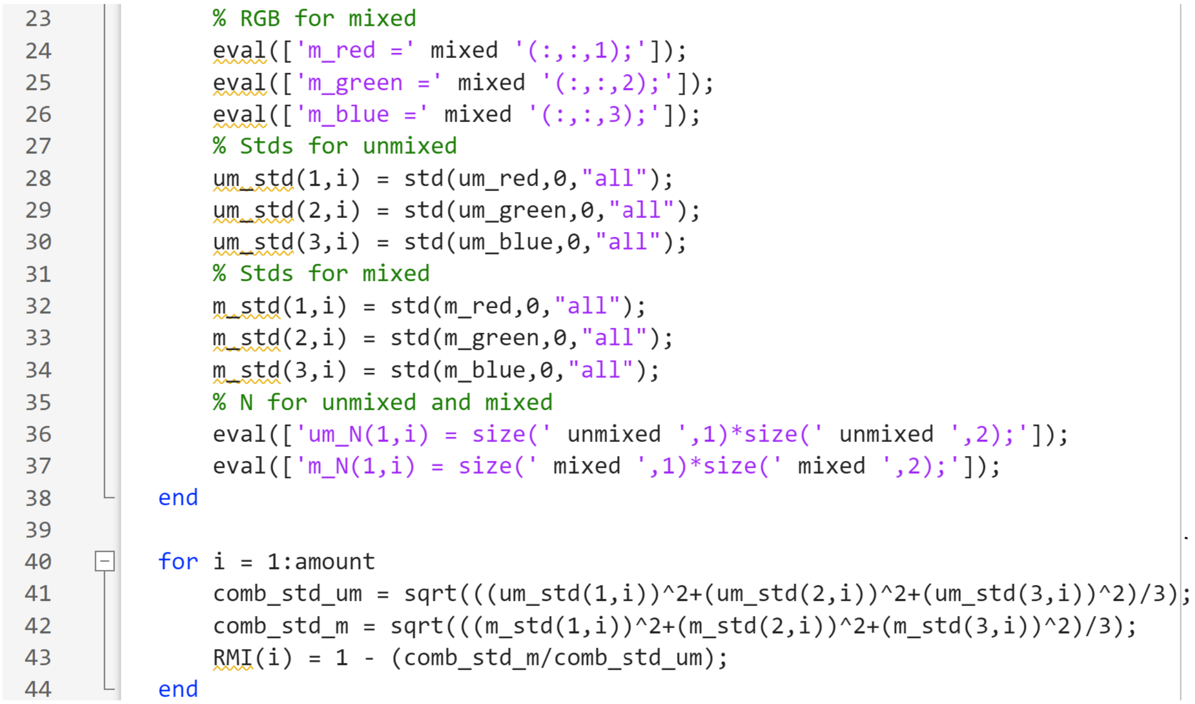
MATLAB Script for Imaging Analysis:



```
clear; clc; close all;

% Means, stds, number of elements, and RMI vectors
amount = 5;
um_std = [];
m_std = [];
um_N = [];
m_N = [];
RMI = [];

% Read in images and convert to doubles
for i = 1:amount
    unmixed = ['unmixed_' num2str(i)];
    mixed = ['mixed_' num2str(i)];
    eval([unmixed '= imread("' unmixed '.jpg");']);
    eval([mixed '= imread("' mixed '.jpg");']);
    eval([unmixed '= double(' unmixed ');']);
    eval([mixed '= double(' mixed ');']);
    % RGB for unmixed
    eval(['um_red =' unmixed '(:,:,1);']);
    eval(['um_green =' unmixed '(:,:,2);']);
    eval(['um_blue =' unmixed '(:,:,3);']);
```



```
    % RGB for mixed
    eval(['m_red =' mixed '(:,:,1);']);
    eval(['m_green =' mixed '(:,:,2);']);
    eval(['m_blue =' mixed '(:,:,3);']);
    % Stds for unmixed
    um_std(1,i) = std(um_red,0,"all");
    um_std(2,i) = std(um_green,0,"all");
    um_std(3,i) = std(um_blue,0,"all");
    % Stds for mixed
    m_std(1,i) = std(m_red,0,"all");
    m_std(2,i) = std(m_green,0,"all");
    m_std(3,i) = std(m_blue,0,"all");
    % N for unmixed and mixed
    eval(['um_N(1,i) = size(' unmixed ',1)*size(' unmixed ',2);']);
    eval(['m_N(1,i) = size(' mixed ',1)*size(' mixed ',2);']);
end

for i = 1:amount
    comb_std_um = sqrt(((um_std(1,i))^2+(um_std(2,i))^2+(um_std(3,i))^2)/3);
    comb_std_m = sqrt(((m_std(1,i))^2+(m_std(2,i))^2+(m_std(3,i))^2)/3);
    RMI(i) = 1 - (comb_std_m/comb_std_um);
end
```

3B)

Requirement: Variable Mixing Ratios

Specification: Mixing ratio can be intentionally changed by ≤ 10% during printing

1.) Prepare syringes with tip pressed to the bottom.
2.) Load syringes with silicone using extraction syringe and adaptor.
3.) Attach syringes to motor mount and run motor until piston is touching the plunger.
4.) Attach length of tubing to end of syringe and run motor until silicone can be seen in the tube.
5.) Measure initial position of silicone in tubing
6.) Run motor for specified setting.
7.) Measure distance travelled down the tube.

Steps	Predicted distance	Syringe A distance	Syringe B distance
80	6.32	4.76	13.78
80	6.32	4.15	19.55
160	12.64	19.16	24.66
160	12.64	11.07	11.07
320	25.28	19.09	21.21
320	25.28	22.47	19.19
320	25.28	25.4	21.68
320	25.28	25.39	28.25

MANUFACTURING AND ASSEMBLY PLAN :

Pre-assembly instructions:

1. The initial 3d printer base was constructed from a Prusa i3 MK3S+. This was performed following the official Prusa build guide from their website. A link to this guide can be found here: https://help.prusa3d.com/category/original-prusa-i3-mk3s-kit-assembly_1128
   Note: The hot end was not attached during the e-axis assembly step, as our mixer replaces it.
2. For a list of external parts see table 10. The following list of parts were 3d printed from PLA filament with the exception of the mixer, which is SLA resin.
    - Base Plate
    - Upper Plates
    - Extruder Mount Left
    - Extruder Mount Right
    - Top Bracket
    - Frame
    - Couplers
    - Mixer Adapter
    - Mixer

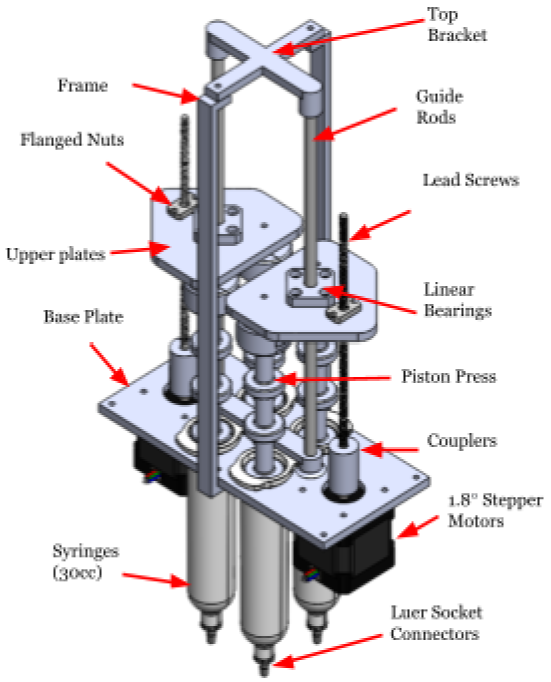


Figure 31a. Completed extruder assembly

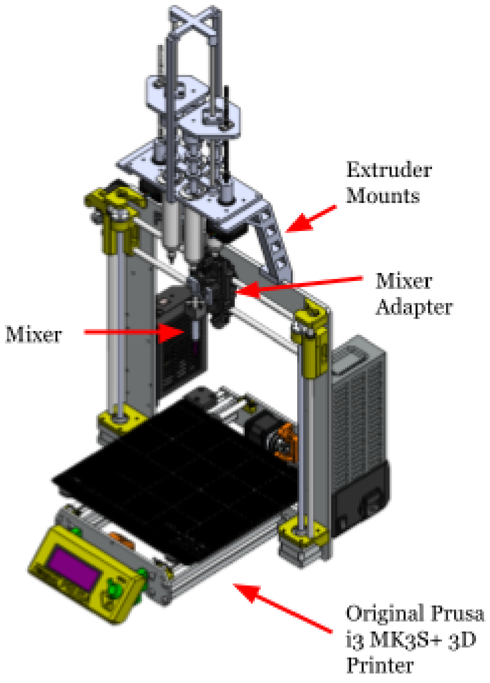


Figure 31b. Completed full assembly

Initial Assembly build guide:

1. Base Plate:
    a. Fasten both stepper motors to the base plate
    b. Press fit the guide rods into corresponding holes.
    c. Use couplers to join lead screws and stepper motors.
2. Upper Plate:
    a. Fasten linear bearings and flanged nuts to the upper plates
    b. Attach piston presses to the top plates.
3. Combining Assemblies:
    a. Slide upper plate assemblies down guide rods until flanged nuts are touching the lead screws.
    b. Turn lead screw to thread it through the flanged nuts until flush with the other end.
4. Frame:
    a. Fasten frames to both sides.
    b. Press fit guide rods into corresponding holes in the top bracket.
    c. Fasten the top bracket to the frame.
    d. Fasten extruder mounts to both sides of the base plate.
    e. Clip the extruder assembly onto the Prusa frame as seen in figure Xb
5. Mixer:
    a. Fasten mixer adapter to the E-axis assembly of the Prusa
    b. Screw a nozzle onto the mixer and insert the mixer into the adapter.
    c. Attach four pieces of tubing to the mixer.
6. Syringes:
    a. Insert a syringe plunger into the end of a syringe.
    b. Load the syringe with desired silicone, careful not to allow air into the cylinder. Note: Make sure to cover the end of the nozzle, as silicone may drip initially. Air can be released from the syringe by leaving it upside down for a time before use.
    c. Insert the syringe into the corresponding hole in the base plate and turn to lock.
    d. Attach a luer socket connector to the end of the syringe and insert into the corresponding tube that leads to the mixer.
    e. Repeat steps 6a-6d with other silicone resins until all four syringes are completed.
7. Electrical:
    a. Plug the motors into the motherboard of the electronics unit.
    b. Run the motors until piston presses are in contact with the plungers and silicone begins to flow down the tubing.

BUILD DESIGN BILL OF MATERIALS

Table 10. BOM for all outsourced components.

Part	Amount	Manufacturer/Provider	Part Number	Cost (USD)
Stepper Motor 1.8 degree	1	Prusa Research	n/a	$38.03
Original Prusa i3 MK3S+ 3D Printer	1	Prusa Research	n/a	$649.00
Syringe Plunger (30 cc)	6	Fisnar/ Ellsworth Adhesives	8401018	$3.00
Piston Press (Green)	3 (20/pack)	Fisnar/ Ellsworth Adhesives	8001009-20	$7.60
Piston Press (Black)	3 (20/pack)	Fisnar/ Ellsworth Adhesives	8001517	$14.00
Lock Tip Nozzle (0.51 mm)	1 (50/pack)	Fisnar/ Ellsworth Adhesives	8001221	$25.00
Syringes (30 cc)	5 (20/pack)	Fisnar/ Ellsworth Adhesives	8001004-20	$15.20
Tubing (10ft)	1	McMaster-Carr	5549K31	$10.60
Luer Socket Connector	4 (10/pack)	McMaster-Carr	51525K213	$4.47
Guide Rods	2	McMaster-Carr	1327K118	$10.86
Lead Screw	2	McMaster-Carr	7549K54	$31.33
Flanged Nut	2	McMaster-Carr	7549K63	$24.57
PVC tubing (50ft)	1	Dernorn/ Amazon	B09B3H1TBS	$11.99
Linear Bearings	2	MiSUMi	U-LHFS0.25	$22.75
Eco flex 10 Silicone Rubber	1	Smooth-On/ Amazon	751635877412	$47.86
Eco flex 50 Silicone Rubber	1	Smooth-On/ Amazon	B00GJ80HIC	$39.16
Dragon skin 20 Silicone Rubber	1	Smooth-On/ Amazon	4336899332	$39.04
Coloring Dyes	1	Smooth-On/ Amazon	88553	$30.83
Static Mixer	10	Duderstadt Fab. Studio	Resin	$5.75
			Total Cost:	$1,304.71

Besides parts outsourced from providers, a lot of components included in the build design were designed and manufactured in-house. Table 11 shows a list of all in-house components:

Table 11. BOM for in-house build design components.

Part	Amount	Manufacturing Process	Material
Plunger Plate	2	Filament 3D Printing	Polylactic Acid Filament
Motors Platform	1	Filament 3D Printing	Polylactic Acid Filament
Snap-On Fixture	8	Filament 3D Printing	Polylactic Acid Filament
Rigidity Pieces	2	Filament 3D Printing	Polylactic Acid Filament
Guide Rod Holder	1	Filament 3D Printing	Polylactic Acid Filament
Mixer Holder	1	Filament 3D Printing	Polylactic Acid Filament
Mixer	10	Resin 3D Printing	Formlabs Tough Resin

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BIOS

Adi Scharf Bio

My name is Adi Scharf, and I am from San Jose, Costa Rica. My interest in mechanical engineering comes from my passion for the environment. Since I was in my Sophomore year of high school, I knew that I wanted to dedicate my life towards working in sustainable technologies. Because I didn't really know in what sub industry of sustainable technology I wanted to work in, I decided that mechanical engineering would be the best route for me. It would give me the best set of tools to go into any field I wanted to. As I learned more about engineering and myself, here at Michigan, I discovered that the sustainable energy industry is what calls me the loudest. Thus, with my mechanical engineering degree I am also pursuing a concentration in energy systems, and a certification in the Program of Sustainable Engineering. For my future plans, my goal is to find a job in industry after graduation in the sustainable technologies sector. At this point in my career, I do not want to limit myself to just the energy sector, to grow as much as possible as a professional as a young engineer. Besides engineering and sustainability, I do have other non-professional passions. I love martial arts, I practiced Muay Thai for 7 years before college, and I am planning on going back into it after I graduate. Additionally, I love to play the guitar and ukulele, during the little free time I get from school work.

Charles Renz Bio

My name is Charlie Renz, and I am from Briarcliff Manor, New York, which is just a short 30-minute train ride from NYC. I was exposed to engineering from a young age, as I always had a fascination with understanding how the world around me works. I have always been interested in exploring new places, solving problems, and building hands-on designs. This naturally led me to want to pursue engineering. I had a difficult time choosing a specific engineering major due to my various range of interests, but I thought mechanical engineering could include a bit of everything. In addition, my dad and grandfather had degrees in Mechanical Engineering, so of course I had to carry on the family legacy. I really enjoy the design and manufacturing process of bringing an idea to life and want to expand on this in the automotive or aerospace industry. Outside of engineering, I always try my best to remain active. I played basketball and soccer in high school and now continue to stay in shape through running and weightlifting. Additionally, I love spending my free time outside in nature and the highlight of my year is always my family's annual hiking trips.

Evan Fassett Bio

My name is Evan Fassett, and I am from Greenville, Michigan. Growing up, I would hear the term "engineer" and I don't believe I began to fully understand what an engineer was until I began middle school. Until that point, all I really knew was that they were supposed to be good at math and science. Well, based on that assumption back then, I had decided I would be an engineer. As I continued through middle school and high school, I gained experience with more engineering-focused projects and I fortunately ended up enjoying it. When I graduated from high school, I had made the decision to pursue a degree in Engineering Physics. After two years at this university, I discovered that I really did not enjoy physics and then switched into Electrical Engineering. Through a combination of remote learning due to COVID, being red-green colorblind, and a developed dislike for signal processing, I changed my major once more to Mechanical Engineering. I always enjoyed learning how things functioned, optimization, drafting, and design, so it makes sense why I enjoy the mechanical engineering projects that I get to work on now. In the future of my professional career, I would like to shift my focus towards product design and manufacturing. Apart from engineering, I really enjoy traveling, seeing new places, trying new cuisines, playing video games, and spending time with my dog.

Zachary Fuss Bio

My name is Zachary Fuss and I am from Hyde Park, Vermont. To tell you a little bit about myself, I love skiing in the winter and spending time outdoors. I have always been heavily interested in how things work and solving problems, even at a young age.I loved to deconstruct things around me and attempt to put things back together (with varying success). Once I reached high school I discovered my passion for STEM-related classes, especially those involving soldering or moving parts. I started a club with some friends to work on an assortment of small broken vehicles like ATVs or go-carts. Engineering always felt like the right track for me, and I had little doubt while I was applying to colleges. Once I arrived at the University of Michigan, I found I enjoyed subjects relating to CAD, robotics, and manufacturing. I could see myself working in many different fields of mechanical engineering at the moment, but I'd especially love to work in automation or robotics. In the future, I'd love to work somewhere in the Midwest where I can ski, such as in Utah, Colorado, or New Mexico. I also used to fly gliders in high school, and I'd love to pursue getting a private pilot's license once I graduate.