Top-Down SLA System Final Report

MSE 127 - Introduction to Additive Manufacturing: Process, Materials, and Designs

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Abstract

Stereolithography (SLA) resins in the right environment can last for months. However, they are susceptible to contamination when exposed to external factors such as UV light, dust, and debris like hair or skin. Additionally, resins settle to the bottom over time and cured resin builds up after every print potentially affecting adhesion of the next print. All these factors change the resin's viscosity and curing property, leading to unpredictability and lower resolution. The most common solution is to discard the resin and clean the vat. However, this can get costly over time. To combat these problems for hobbyists and makers, we have developed a stirring system for top-down SLA. Our stirring system incorporates a blade that maintains a uniform mixture of resin throughout the vat, prevents settling, reduces air bubbles, and is cost effective. Our stirring system is necessary in top-down SLA to help prolong the resin usability lifetime, minimize wastage, and ensure the production of dimensionally consistent parts.

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Original Whitepaper

In the context of our MSE 127 final project, we are pursuing the development of an innovative top-down stereolithography (SLA) system. Our primary goal is to gain a deeper understanding of the intricacies of SLA printers and subsequently implement improvements. Currently, SLA printers encounter various challenges, such as resin spillage, viscosity problems, challenging support removal, poor layer adhesion, and UV light-related issues like under or over curing. Our team has opted to focus on the problem of inconsistent viscosity within SLA printing resins. Resin viscosity plays an important role in ensuring optimal material flow during the 3D printing process. When resin viscosity is excessively high, it can lead to incomplete prints, surface irregularities, or clogs within the printer's system due to improper flow. Conversely, if the resin viscosity is too low, it may result in excessive dripping or diminished print quality. To address this issue, we are designing a mechanical stirrer mechanism capable of stirring the resin to maintain a consistent viscosity throughout the vat, thereby enhancing printing outcomes. Additionally, we have opted for a top-down approach to achieve faster printing times and reduce the overall resin requirement.

To address this challenge, we propose the construction of a comprehensive and detailed 3D model of our top-down SLA system utilizing SolidWorks software. Furthermore, we intend to conduct simulations, such as finite element analysis (FEA), on our design to identify and mitigate potential vulnerabilities. Our hope is to potentially fabricate our design leveraging the resources available at the Jacobs Design Institute. Through our participation in Engineering 29, we have secured Makerpasses, which will grant us access to the metal shop, TIG welding tools, laser cutter (Fablight), and various 3D printers, if required.

Our group aims to construct the top-down SLA system, incorporating a novel stirrer mechanism to address the issue of resin consistency throughout the vat photopolymerization technique commonly employed in top-down SLA printing. Unique aspects of our project include the development of the stirrer and the undertaking of building the entire 3D printing system from scratch. Based on our current research, we are not aware of any existing solutions specifically tailored to address viscosity issues encountered in vat photopolymerization techniques, particularly in the context of top-down SLA methods. Potential limitations to our approach include the challenge of developing a fully effective stirrer design to mitigate the viscosity problem and potential monetary constraints that may arise during the fabrication phase.

For our midterm deliverable, we aim to present a completed preliminary computer-aided design (CAD) model of our top-down SLA system. Our final deliverable will comprise a fully finished and comprehensive 3D model of our SLA system, accompanied by the potential fabrication of a physical prototype. The project costs will be determined based on the quantity of materials required to bring our 3D system design to fruition within Jacobs Hall. We anticipate that our primary expenses will be associated with the procurement of necessary materials.

Our goal is to design and possibly fabricate a function Top-Down SLA 3D printing system with a novel stirring mechanism to help enhance consistent viscosity. This will help with ensuring optimal material flow within the printing process, minimize the chances of over-curing or under-curing, and help combat bed adhesion issues. This project will allow all group members to gain hands-on experience with creating an advanced, top-down additive manufacturing system from scratch, as well as familiarize and delve deeper into various additive manufacturing concepts covered throughout the semester in the class.

Introduction

Top-Down Stereolithography (SLA) is an additive manufacturing technique that has garnered lots of attention over recent years, due to its ability to produce high-resolution, complex and accurate parts. It's commonly used across several fields, from medicine to dentistry, and from engineering to product design. Typically, stereolithography printers use a bottom-up approach in which a very powerful laser or projector is placed beneath the liquid resin vat, thus curing the resin layer-by-layer as the build platform gradually rises. However, top-down SLA has recently risen as a more viable approach for certain use cases.

In top down SLA, the build platform is positioned above a transparent window, and the photosensitive resin is selectively cured from the top-down using a high intensity light source, such as digital light processing (DLP) or a laser, as shown in Image 8. This enables higher printing speeds compared to bottom-up approaches. Also, top-down SLA is generally superior for large-scale printing applications.

However, Top-Down SLA does have its own set of challenges. The open resin vat in the top-down SLA system tends to require more resin consumption compared to bottom-up counterparts. Also, top-down SLA tends to struggle with producing extremely high precision parts identical to the level that bottom up additive manufacturing approaches can produce. The difference is very small, but there is a difference in precision nonetheless.

Our team is composed of two freshmen, both majoring in mechanical engineering. Aarush is interested in a career in the aerospace/defense industry, and took MSE 127 to learn more about additive manufacturing, or as he knew it at the time, 3D printing. Jaden is interested in a career in the mechatronics industry and took MSE 127 to improve upon his FDM prototyping abilities, but has been introduced to many other additive processes.

Given the final project assignment, we decided to pursue a hands-on project that would allow us to get our hands dirty, doing more experiential work rather than theoretical work. It was also our first time using 3D printers to fabricate a prototype from scratch, so we carefully decided ideas within our knowledge base. Our team's initial idea was to create a Top-Down Stereolithography (SLA) system from scratch. However, this idea was scrapped due to budgetary and time constraints. Instead, our team decided to pursue an innovative stirring system for Top-Down SLA 3D printers. Our goal was to solve the problem of inconsistent viscosity within SLA printing resins by incorporating a novel stirrer mechanism to address the issue of resin consistency. Specifically, residual resin builds up after every print in Top-Down SLA systems. The continuous exposure to UV light, as well as dust and debris changes the resin curing properties. It also makes the resin more susceptible to external contamination, effectively lowering resin's intended shelf life of numerous months. Contaminated resin is also less predictable, which again increases the chances of a faulty 3D printed part. Our stirring system, if effective for its intended purpose, would maintain uniform resin mixture throughout the vat, an even temperature, prevent the resin from settling, reduce air bubbles, be easy to use and integrate into existing top-down sla systems, be gentle enough to not damage FEP (Fluorinated Ethylene Propylene), and be cost effective, all while improving the final print quality, allowing for dimensionally consistent prints, and extending resin usability and lifetime while also minimizing resin wastage. Throughout this report, the terms stirrer and blade will be used interchangeably.

Literature Review

Through intensive online research, we found a few papers relating to the problem we are trying to address. The first paper was about 3D printing of ultra-high viscosity resin by a linear scan-based vat photopolymerization (LSVP) system[1]. In traditional SLA systems, resin viscosity must remain under 5000 cps for the leveling mechanism to function properly. The LSVP system needs rollers to separate cured resin from the resin tank, taking away the need for a leveling mechanism and thus allowing for high-viscosity resin use. This innovation surpasses one SLA system limitation and could potentially enable the use of a wider variety of resins with improved mechanical properties. The paper's key finding is that the difficulty in printing high viscosity resins comes from the leveling of the resin and the film's cured parts. Traditional 3D printing techniques commonly use a recoater or sweeper to spread the resin. Although, the excessive shear force tends to affect the cured part's original position, leading to part failure. To address the issue, the LSVP system uses a scanning approach. This allows it to process UV-curable resins with high-viscosity while keeping the same level of printing efficiency. However, the paper's authors do acknowledge that the level surface was lower than expected for high-viscosity resins.

The second paper was about the effect of the resin viscosity on the writing properties of two-photon polymerization[2]. It discussed the challenges and possible solutions for implementing a continuous top-down SLA 3D printing process. The key findings of the paper relevant to our problem statement are the rapid curing of resin flow, couscous flow effects, surface tension effects, the purpose build platform, and an inclined built platform. During continuous exposure at the time of the build platform's descent, new resin flows into the exposure area. This new resin undergoes immediate curing prior to flowing past the exposure boundary, resulting in weakly connected layers and an overall porous object. On the other hand, resins with higher viscosities needed more time to flow laterally over the build platform in order to supply material for the first layer and all that followed. This occurred in individual and continuous operation, but was disruptive to the printing process. According to the paper, the resin's flow and distribution of resin was found to be dependent on its surface tensions. The involved researchers observed processes being disrupted during early stages of the experiment due to a combination of surface tension and virtuous flow. A porous build platform enabled consistent resin inflow during the start of the print, which led to more successful primary layers compared to a solid build platform. On the other hand, an inclined build platform was also found to be a potential mitigating factor improving the continuous top-down SLA process via resin flow facilitation. The researchers' final conclusion was that using a porous or inclined build platform could potentially resolve issues and problems relating to inconsistent resin viscosity in top-down SLA systems, specifically in the areas of rapid curing, poor lateral resin flow, and the effects of surface tension.

The last paper was about Computational Fluid Dynamics Modeling of Top-Down Digital Light Processing Additive Manufacturing[3]. It discussed the impact of fluid viscosity on the stability of the fluid interface in top-down digital light processing (DLP) 3D printing systems. Their key findings suggested that by increasing the fluid viscosity from 0.05 to 1 Pa-s, the fluid interface needed more time to reach a stable state. Using the reference parameter, stabilizing the fluid interface took about 16.5 seconds. For a fluid viscosity of 1 Pa-s, a maximum stability time of 51 seconds was achieved, through optimization, for a thickness deviation of 2 μm. Additionally, increasing traveling speed from 1 to 2 mm/s resulted in a diminishing trend for the stability time. The findings show the significance of fluid viscosity in top-down DLP 3D printing systems. Higher viscosity resins need more time to stabilize, which could impact consistency and print quality. The paper's authors show that through parameter optimization such as traveling speed and layer thickness, stability time can be maximized to mitigate challenges posed by inconsistent resin viscosity. The findings from this study provide valuable insights that can help guide the development of more robust and reliable top-down DLP 3D printing systems, especially to address variable resin viscosity.

Our intensive review of literature relating to inconsistent resin viscosity challenges in Top-Down systems showed the main knowledge gap to be in addressing effective solutions to solve the inconsistent resin viscosity problem in Top-Down printers, specifically Top-Down SLA, especially on a larger scale. Although previous solutions, such as roller-based systems for high-viscosity resins and platform modifications for continuous top-down printing give us some insights, there still exists a need to get a better grasp of the relation between resin properties, process parameters, and overall system design in order to create robust and reliable Top-Down SLA systems that produce consistent resin viscosity for a varied range of viscous resins. Future research should aim to focus on the efficiency of proposed solutions, as well as exploring the avenue of developing additional novel solutions to address the problem statement.

Methodology

The first step of our process was deciding our criteria for what makes a successful stirring system. We wanted to develop a system that extends resin usability lifetime and allows for dimensionally consistent prints. Additionally, it must be cost effective and easy to use. From this criteria, we researched different design approaches for mixing the resin. The most common and doable approaches included ultrasonic, magnetic, and mechanical stirrers. We found ultrasonic mixers to be the most efficient method to maintain a homogenous mixture because it does not take up much space in the vat, is powerful, and has no moving parts that can fail. However, ultrasonic mixers did not meet our criteria of being cheap. Thus, we went with a mechanical approach to which we could easily assemble and test. Having a mechanical blade is simple and thus reliable.

To manufacture the system, an SLA printer could be used and our CAD file would still work for it, but we thought FDM would be best. The use of PLA is cheap, durable, and doesn't degrade in the uncured resin. The blade, motor housing, and rail are all 3 different parts that can be FDM printed. The rollers of the motor housing have been designed to be FDM printed with the motor housing by incorporating holes around the pins connecting the rollers. Some disadvantages of FDM printing our parts is stringing that must be removed and the low resolution of some of the details our design entails.

Results and Discussion

Image 9 shows the complete CAD of our stirring system. The whole rail is supposed to be attached to the side of a top-down SLA system (Image 8). The width is about an inch, thickness depends on the size of the motor, and the height can vary depending on the specific top-down SLA system. Our design uses lots of filets to reduce sharp edges which FDM printing can have troubles with. For the design of the blade we decided on an impeller design (Image 7) because it can achieve a much faster speed (if needed) than a propeller design. Impeller blades are designed for radial and axial flow which makes them efficient at mixing fluids. With the blade we have a motor that sits on a motor housing connected to a rail placed on the side of the vat. The motor and blade go up and down the rail with the height controlled by changing the height of the bed. The motor housing has a set of 6 rollers that limits the degrees of freedom to just up and down the rail. Our product works by setting the blade to a desired height and turning on the motor to mix the resin before each print. This will create a homogenous mixture of resin with the hopes of improved print quality.

Through our additive manufacturing process selection analysis, we decided to go with FDM to print our stirrer. We decided to utilize a Bambu P1S 3D printer available to us through one of our clubs, due to its high-end print capabilities and optimized slicing software. Additionally, the enlarged print bed size was necessary to print larger scale blade designs to conduct our experiment. However, the final parts can all fit and be printed on a normal FDM bed.

For our blade experiment, the materials we needed consisted of a transparent container (shown in Image 1), water, food coloring, our 3D printed novel stirrer designs (shown in Image 2), a moderately powerful motor, an ESC (Electronic Speed Controller), an electronic stopwatch, and a Ruler/Measuring Tape. The transparent container allowed us to observe our blade's effectiveness for our makeshift resin solution. The water mixed with food coloring would create a water-based solution to mimic resin behavior. Our 3D printed novel stirrer design is the product we are testing in this experiment. A moderately powerful motor and the ESC were used to control motor speed.

The electronic stopwatch was used for data collection purposes, and both a ruler and measuring tape were used to measure the depth of water with the purpose of keeping it constant throughout different trials during the experiment.

Our procedure consisted of the following steps: we began by filling the tub with water to a certain level. We wrote this level down (3 cm depth), as this was kept constant throughout all trials. We then added a few drops of food coloring to the water to create a visually distinct liquid. An example can be seen in Image 5. This helped in distinguishing the movement of the "resin". Once we placed the stirrer at a certain height above the water surface and ensured the stirrer was positioned vertically, we submerge the stirrer into the tub. We connected our esc and motor, and connected the motor to the blade. We ran the motor at a slow enough speed as to spin the blade without causing bubbles in our makeshift resin mixture. and waited for the water to return to a flat state. As soon as we started the motor to power the stirrer on, we started our stopwatch simultaneously. The 'before' state of the mixture for the 10 drop resin viscosity and 1 drop resin viscosity can be seen in Images 3 and 5, respectively. The 'after' state of the mixture for the 10 drop resin viscosity and 1 drop resin viscosity can be seen in Images 4 and 6, respectively. We stopped the stopwatch once the food coloring had been fully dissolved into the water and the water returned to a flat state. We repeated the above steps several times to get an average of the results and get consistent data, canceling out all outliers. Then we repeated the above steps again, and included the repetition in the seventh step. For the second step, we varied the number of drops of food coloring put into the water. This represented varying viscosity ranges for the resin.

Analyzing our graphs from Figures 1 and 2 that were plotted with data from Tables 1 and 2 showed an increasing trend, indicating that it takes longer for solutions with higher 'viscosity' to be completely mixed into the water and for the water to return to a flat state after the blade and motor has been in use. Note that in the Figure 1 and 2 graphs, time represents the number of seconds it took for the food coloring to be completely mixed in the water, and then return to a flat state. Additionally, in the Figure 1 and 2 graphs, the makeshift resin viscosity is represented by varying amounts of food coloring dropped into the water. This suggests that our blade works as expected in regards to being able to thoroughly mix different resins for Top-Down SLA systems. This experiment provides a general framework for us, as well as future researchers to evaluate the effectiveness of our blade design. Through analysis between the solution's viscosity and the time, we were able to observe how our blade was functionable for its intended purpose.

Some external factors we realized we needed to consider after our preliminary analysis were that our experiment was quite simplified, so we needed an experiment to test the technical performance of our blade in an actual environment. Also, the actual composition of resins being different from our makeshift resin using a water and food coloring solution. Actual resin could show shear thinning behavior, where its viscosity decreases with shear rate.

To evaluate the technical performance of our fabricated product in a real world environment, we designed an experiment to test the print quality of a crystalline structure printed with Top-Down SLA, both with the use of our blade and without. Unfortunately, due to time constraints and lack of access to Top-Down SLA systems, we were unable to finish this experiment. However, if similar studies are to be conducted in the future, we'd highly recommend conducting this experiment for data and results in a real-world context.

Our print quality experiment required a Top-Down SLA printer, the 3D printed novel blade design, and the STL file of the crystalline structure. Our procedure consisted of the following steps: we began by slicing the STL file according to the corresponding Top-Down software. Then, we ensured the print settings and the print parameters were correct, and started our print. Once the print completed, we examined its precision under a microscope, and then repeated the previous steps for multiple data points. After ensuring the blade was properly integrated within the Top-Down SLA system, we repeated all of the previous steps (including the repetition) to generate prints with blade usage and examine their precision. We expect the results of the experiment to be along the lines of: Top-Down SLA prints using the blade will exhibit greater precision than similar prints on the same printer without blade usage.

Recommendations for Future Work

The limitations of our product is size and the inability to cleanse the resin of debris such as dust, skin, and hair. Instead of a stirring system, we could look into a filtration system much like a fish pond that would allow the resin to flow and mix through a filter. This would be effective at actually cleaning the resin and with our knowledge of stirring, we could incorporate both ideas to allow for a clean, homogenous mixture of resin. With regards to size, our stirring system can always be improved by decreasing its dimensions to allow for more space in the vat for printing. To do this, looking into ultrasonic mixers more and finding a way to reduce its costs could be beneficial. An ultrasonic mixer that is embedded to the bottom of the top-down SLA printer would be most effective, but would require a lot of resources, testing, and innovation to reduce costs. Another alternative would be a smart SLA system in which only the resin needed is expelled from the tank much like a bottom-up SLA printer. Using electronics for data collection would be the best approach forward.

Conclusion

The development of a stirring system for top-down Stereolithography (SLA) printers addresses critical challenges faced in additive manufacturing, particularly in maintaining resin viscosity and print quality. The project aimed to extend resin usability, minimize wastage, and ensure dimensionally consistent prints by combating issues such as settling, contamination, and inconsistent curing properties. Through extensive research and experimentation, our team designed and tested a mechanical stirring system capable of maintaining a uniform resin mixture throughout the vat. The system, incorporating a novel blade design, showed promising results in effectively mixing resins of varying viscosities with experimental data indicating that the stirring system reduced settling and improved homogeneity, leading to enhanced print quality. While the project encountered limitations, such as size constraints and the inability to cleanse resin of contaminants, valuable insights were gained for future improvements. A filtration system could be added along with our stirring system for future improvements. More testing through experiments must be done to understand the relationship between properly treated resins and print resolution even more. In conclusion, the development of the stirring system represents a significant mechanism in top-down SLA printing technology. By addressing resin viscosity challenges, the system offers potential applications in various industries requiring high-resolution and dimensionally accurate parts.

References

[1]Weng, Zixiang, et al. “3D Printing of Ultra-High Viscosity Resin by a Linear Scan-Based VAT Photopolymerization System.” *Nature News*, Nature Publishing Group, 18 July 2023, www.nature.com/articles/s41467-023-39913-4.

[2]Zandrini, T., et al. “Effect of the Resin Viscosity on the Writing Properties of Two-Photon Polymerization.” *Optica Publishing Group*, opg.optica.org/ome/fulltext.cfm?uri=ome-9-6-2601&id=412684. Accessed 6 May 2024.

[3]Moghadasi, Hesam, et al. “Computational Fluid Dynamics Modeling of Top-down Digital Light Processing Additive Manufacturing.” *MDPI*, Multidisciplinary Digital Publishing Institute, 26 May 2023, www.mdpi.com/2073-4360/15/11/2459.

Appendix

Link to final presentation

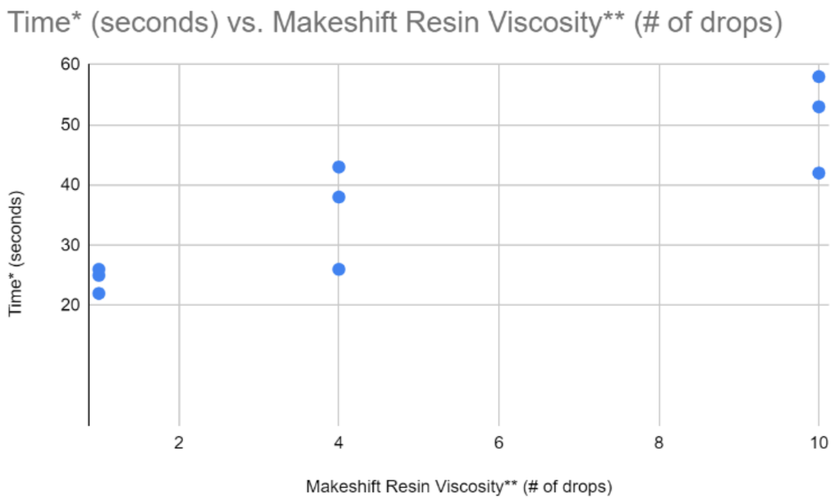

Figure 1: Scatterplot of Time vs Makeshift Resin Viscosity

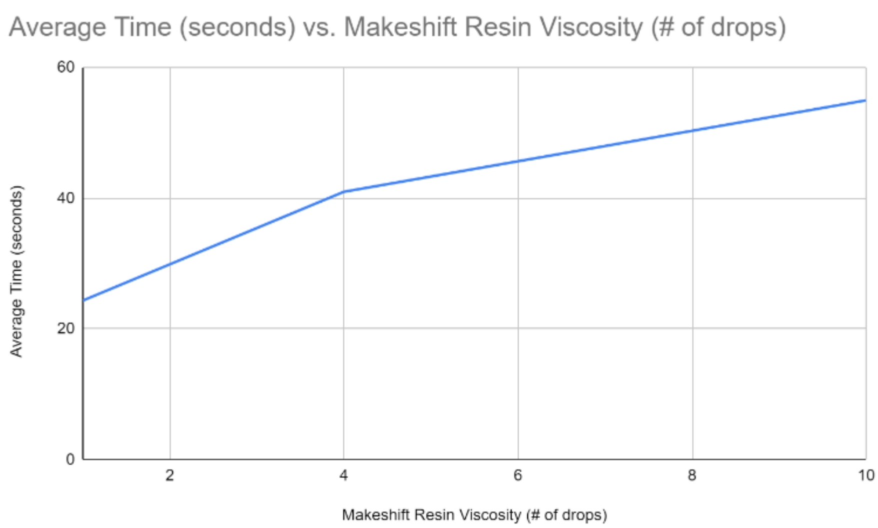

Figure 2: Line Graph of Average Time vs Makeshift Resin Viscosity

Makeshift Resin	Time* (seconds)
1	22
1	25
1	26
4	26
4	38
4	43
10	42
10	58
10	53

Table 1: Makeshift Resin Viscosity (# of drops) vs Time for Complete Dissolving (seconds)

Makeshift Resin	Average Time (seconds)
1	24.33
4	41
10	55

Table 2: Makeshift Resin Viscosity (# of drops) vs. Average Time for Complete Dissolving (seconds)

Image 1: Transparent container used to conduct Blade Experiment

Image 2: 3D Printed Final Blade Design

Image 3: 10 drop Mixture before mixing with blade

Image 4: 10 drop mixture after stirring with blade

Image 5: 1 drop into water

Image 6: Makeshift Resin Mixture (1 drop) after Stirring with Blade

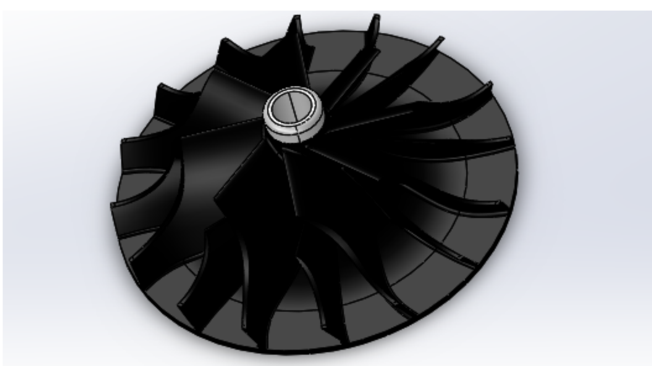

Image 7: CAD Rendering of Final Blade/Stirrer Design

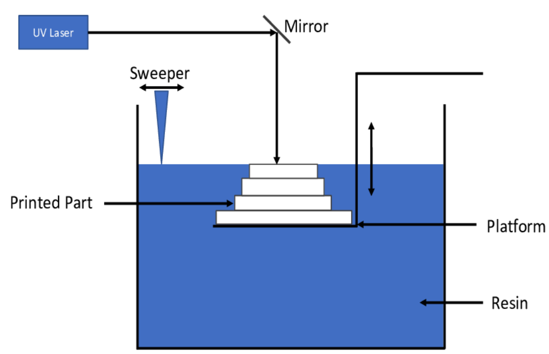

Image 8: Top-Down SLA Diagram

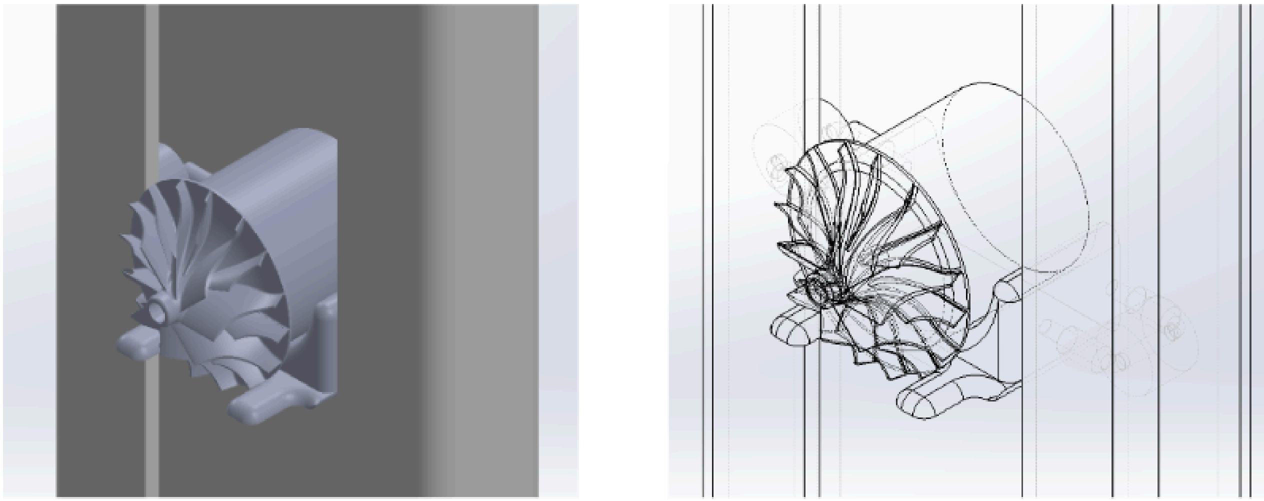

Image 9: CAD Rendering of Blade with Motor Housing attached to Rail System

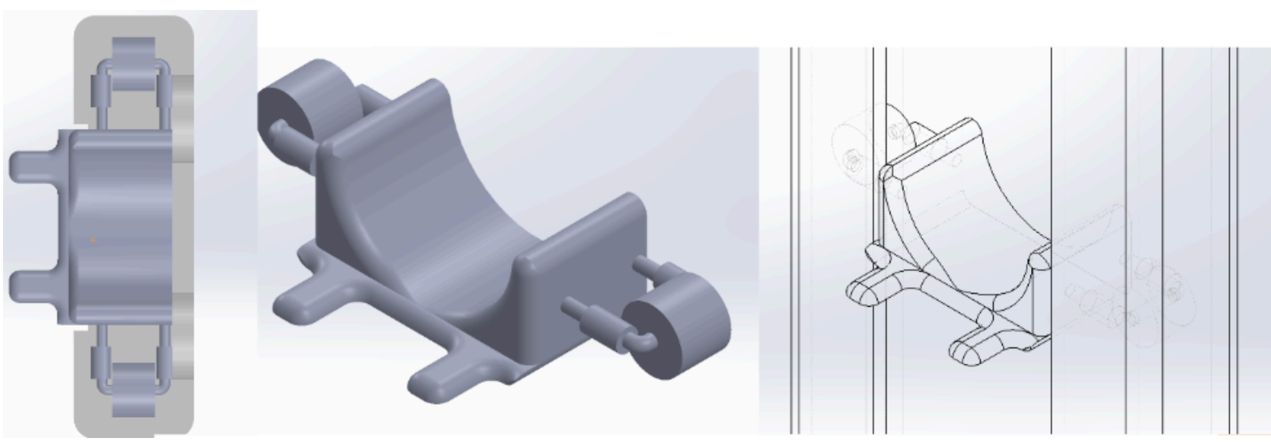

Image 10: CAD Renderings of Motor Housing and Rail System