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Multi-material 3D Printing with Hybrid Direct Ink Writing-volumetric Additive Manufacturing (DIW-VAM) System

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MULTI-MATERIAL 3D PRINTING WITH HYBRID DIRECT INK WRITING-VOLUMETRIC ADDITIVE MANUFACTURING (DIW-VAM) SYSTEM

By

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B.S University of Central Florida 2021

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ABSTRACT

The rapid growth of 3D printing has led to many new iterations of additive manufacturing techniques. However, the current 3D printing techniques encompass only one printing method and have gradually expanded the ability to print multiple materials simultaneously. In this research, a hybrid 3D printing system is created by integrating direct ink writing (DIW) into volumetric additive manufacturing (VAM) to achieve multi-material printing. Compared to traditional DLP and SLA printing systems, the hybrid DIW-VAM system can create parts 95% faster. Meanwhile, the developed hybrid system takes advantages of DIW's precision to suspend a secondary liquid resin through extrusion into a glass cylinder containing a primary UV photopolymer resin. The suspended UV photopolymer resin has a tensile strength of 50 MPa while the primary UV photopolymer resin is a flexible photopolymer material with a tensile strength of 5.5 MPa. Such a dual-material printing capability can create a part with two different mechanical properties in a 3D-printed structure. From the perspective of potential applications, the hybrid DIW-VAM printing system could create artificial human organs with complex geometries and internal structures that are made of different materials. It can also be used to create interlocked or embedded structures such as building a soft flexible structure over a curved hard-core material or integrating a sensor network into 3D-printed structures.

ACKNOWLEDGMENTS

I would like to begin by expressing my deep gratitude to Dr. Jihua Gou for their invaluable guidance and support throughout the duration of this project. Their insightful input and critical thinking have challenged me to stretch my limits and strive for excellence, and I feel fortunate to have had the opportunity to learn from them.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABELS

CHAPTER ONE: INTRODUCTION

1.1 Motivation

3d printing has been around since the 1980s. It is a process that turns 3D models into solid objects in a method known as additive manufacturing. Additive manufacturing has been used heavily in rapid prototyping as it creates the parts using an automated controlled process. The realm of additive manufacturing is a rapidly growing sector that adapts new challenges to advance current techniques of fabrication. Taking a closer look at the many printing methods, the most common printing methods only use one type of printing method and creating a part with two different materials is still rudimentary. This lack of expansion in combining different methods with dual material abilities is the motivation behind this research. Harnessing the strengths of two different methods and combining them to create a multi-material 3D printing hybrid system will push the borders of 3d printing technology.

When combining two printing methods, picking two methods that can take the most advantage of each other is vial. Volumetric method printing and direct ink writing were selected to be the base of the hybrid system. VAM was selected for its fast printing which can solidify a 15 mm high solid cylinder with a diameter of 10 mm in 50 seconds compared to SLA which given the same part will take up towards 18 minutes to complete. VAM also eliminates the need for support structures due to the parts being suspended in the liquid resin. One strength of DIW is its ability to be modular. DIW can be modified to deposit accurate amounts of materials of any kind to precise locations with repeatability. Using these two methods in conjunction gives the ability to deposit liquid resin inside the base material of the VAM print area. Using different materials in each printing method can achieve a dual material print.

This idea of combining two printing methods can expand the horizon of 3d printing and can be used in many applications, such as creating organs that are made of different material properties in which can be printed on demand and used to creating testing apparatus. It can also be used to create fast prototyping tools without the need to have a two-step process. Composite materials can be created on demand with different resin types and can print complicated geometries to enhance the physical properties of the parts. The ideas are limitless and different methods of printing can be combined to create other iterations to achieve different outcomes.

1.2 Volumetric Printing

This project aims to harness this technology of near-instantaneous fabrication to create a hybrid system capable of dual material printing. The VAM side of this hybrid system uses a photocurable resin that when exposed to sufficient UV light between 400 to 405 nm wavelength range will cure into the desired part in less than one minute. This concept works by exposing resin to a UV projection. Due to the center of the resin getting a consistent ray of UV energy, the part starts to propagate from the center outwards.

The key to volumetric printing is accuracy and precision due to the UV light curing in the middle of the projection. If the projectors are not inline, the overlapping images will interfere with each other and create a distorted part. The biggest obstacle of this project was to create a system that can be modular, accurate and precise in order to have the ability to produce repeatable results. With this proof of concept, the methodology can be enhanced by introducing feedback loops to adjust the projectors in order to counteract the unalignment.

The advantage of using volumetric printing over SLA layer by layer printing is the ability to create parts that are suspended in fluid which allows to print structures without supports. This greatly reduces the amount of wasted material and print time. By utilizing the fluid suspension properties of VAM, it can also be used to our advantage when adapting the DIW system.

1.3 DIW Printing

Direct Ink Writing (DIW) is a 3D printing technique that uses a robotic deposition system to create objects layer by layer, using a nozzle or a syringe to extrude a viscous material. The material is usually a polymer or a composite material that is deposited onto a substrate in a controlled manner. The process can create complex shapes with high resolution and accuracy. DIW can be used to create a wide range of objects, including biomedical implants, sensors, soft robotics, and electronic devices. It has several advantages over other 3D printing methods, such as the ability to create structures with varying material properties, the ability to print overhanging structures without support, and the ability to print complex geometries with high precision. One of the challenges of DIW is the selection of suitable materials that can be printed, as well as the optimization of printing parameters such as the nozzle diameter, printing speed, and temperature. However, with ongoing research and development, DIW has the potential to revolutionize manufacturing in a variety of fields, from medicine to electronics to aerospace.

The mechanical method chosen to achieve a hybrid system capable of a dual material part is DIW due to its ability to deposit any type of material with great precision and its ability to be modified to accommodate for any type of system. DIW will be working in conjunction with two projectors that are located 90 degrees from each other and rotated around the resin vat which is a cylindrical glass container that holds the resins. The DIW system is mounted on top of the VAM system as to not interfere with the rotation of the projectors. These projectors emit a 405nm wavelength which is the curing wavelength for the resins. The DIW system uses a R.A.M.P 1.4 board with marlin software. This board controls a modified syringe pump to dispense the resin through a tube. Using a 22-gauge needle, the resin is deposited inside the base material and due to the materials' similar density,–stays in place. Curing time is a critical part of the hybrid dual material method due to the secondary resin diffusing in the primary resin over time. Prints took 30 to 50 seconds to cure. The two materials that were chosen for this application were Superflex flexible resin (80A) and Elegoo Standard UV resin. These two off the shelf resin gave the best results with the projectors power outputs.

The difficulty of having a dual material volumetric printer is the logistics of having multiple variables aligned and working accurately. The chemical balance is another issue facing this current technology as sometimes two different materials are not compatible or adhere correctly to each other.

1.4 Objectives

The main objective of this research is to create a hybrid system of a 3D printer via volumetric method with DIW to have the capability of printing a part that consists of two different materials. A series of samples are to be printed using the volumetric printing method and the dual material method that utilizes a hybrid technique of DIW and volumetric method. Comparing these samples to DLP printing will show the difference in strengths between the exposure time, material makeup and printing method. The major focus is to establish a proof of concept of early development for a multi-material 3D printing method with hybrid direct ink writing which can form a foundation for scaling up and establish a baseline for methods that combine two different styles of 3d printing. This printer would be an important representation of an insightful approach to solving some of the current commercial 3D printer limitations which are complexity, portability, and flexibility. By creating a printer that utilizes volumetric capabilities of rapid printing with DIWs precise depositing abilities, the potential users would benefit significantly in the ways just mentioned and in terms of cost, time, and adaptability. Potential end users include medical and research professionals, anyone in the manufacturing industry that needs rapid and precise models, or the general consumer that wants a unique and fast printer in the comfort of their own home. The final version of this printer will need to have extreme stability, a much more sophisticated computer and software system for projections, more powerful and customized projectors, a user-friendly interface and controls, and the ability to print much larger objects.

1.5 Thesis Outline

Chapter two will consist of an overview of the volumetric printing method and how it has progressed over time. VAM will be discussed further in greater details and elaborated on the difference from other styles of printing. Chapter three will discuss the three iterations that have been developed. It will also include the problems encountered during each iteration and how the following iteration overcame these obstacles. Chapter four will show the testing procedures, including how the sample where created, tested and how the data was gathered and implemented. Finally, chapter five will wrap up all the finding and highlight more improvements for future iterations.

CHAPTER TWO: LITERATURE REVIEW

2.1 3d Printing Techniques

To improve upon the current 3D printing methods, the shortcomings of each method must be identified. Stereolithography (SLA) is a curing process that uses a single laser beam, located directly above the printer tank, to solidify each layer of the desired 3D object. SLA trades resolution quality for print speed and even then, it is still one of the slower 3D printing processes. Digital Light Processing (DLP) uses a projector, located under a transparent tank containing photosensitive material, to cure whole cross sections of a 3D object. DLP is quicker and capable of higher quality prints than SLA but again, the faster the print the lower the quality. Continuous Liquid Interface Processing (CLIP) is, essentially, an improved version of DLP. Instead of projecting cross-sections of an object layer-by-layer, this method projects a sequence of cross sections so quickly that it is considered a superposition video. CLIP has the fastest speeds and possibly the best quality of the 3 but ends up trading speed for the overall strength of the printed object. In Direct Ink Writing (DIW) 3d printing, uses a nozzle or syringe to extrude a viscous material, such as a hydrogel or a polymer solution, onto a substrate in a controlled manner. The material is deposited layer by layer, with each layer being cured or solidified by various means, such as exposure to ultraviolet light or a change in temperature. The nozzle is controlled by a Standard Tessellation Language (STL) file, which directs the nozzle's movements to create the desired shape. Lastly Volumetric 3D printing is a technique that uses light to create a three-dimensional object by solidifying a liquid material. Traditional 3D printing methods rely on layer-by-layer printing, volumetric 3D printing works by projecting image or pattern onto a container of liquid resin, causing it to solidify all at once. The process involves the use of a rotating cylinder filled with a transparent photosensitive liquid. As the cylinder rotates, a projector projects a 2D image onto the liquid from different angles, creating a 3D pattern. The areas that are exposed to the light from the projector solidify into a solid object, while the remaining liquid stays in its liquid form. Volumetric 3D printing has the potential to create objects much faster than traditional 3D printing methods and can produce objects without the need of support structures. However, the technology is still in its early stages of development and is not yet widely available.

Additive manufacturing has changed significantly over the past 40 years by directly improving upon larger Resin-based 3D printers with modern SLA and DLP printing forms, each with their own unique usage cases. The current layer-by-layer based DLP 3D printers can undergo similar improvements by changing to an all-at-once form that aims to immensely reduce printing times. This assessment intends to address the specific techniques and relevant tools we can use to produce a base of which to fabricate this unique printing form.

2.2 Hybrid 3d Printing

Hybrid 3D printing refers to the use of multiple additive manufacturing techniques, such as Direct Ink Writing (DIW), Stereolithography (SLA), and Selective Laser Sintering (SLS), in combination with another additive manufacturing technique. By combining different techniques, hybrid 3D printing can enable the production of parts with more complex geometries, higher precision, and better mechanical properties than traditional 3D printing alone.

Direct Ink Writing with Laser Engraving (DIW-LE) is a technique which combines DIW 3D printing with laser engraving to create precise, intricate designs on the surface of the printed object. The DIW process is used to print the object, while the laser engraving process is used to create fine details or patterns on the surface.

Multi-Material Jetting (MMJ) combines inkjet printing with 3D printing to create objects with multiple colors or materials. The inkjet heads deposit colored or transparent inks onto the build platform, while the 3D printing process is used to print the object with a clear or white material.

Continuous Liquid Interface Production (CLIP) with DLP 3D Printing is a technique which combines CLIP, a type of 3D printing that uses a liquid resin and UV light to create objects, with Digital Light Processing (DLP) 3D printing to create objects with high resolution and mechanical properties. The CLIP process is used to create a continuous liquid interface, while the DLP process is used to cure the resin at a high resolution and speed. The combination of 3D printing manufacturing methods offers more design freedom and flexibility in terms of material selection and part customization, making hybrid 3D printing an attractive option for applications ranging from aerospace and automotive to medical devices and consumer goods.

Valentine et al. [2] conducted a study in Hybrid 3d printing of soft electronics. Their method used direct ink writing, which is a form of DIW printing, that a liquid ink that is dispense out of a small nozzle in a controlled flow rate like DIW. This in combination~~s~~ with an automated pick and place surface mount component created a soft wearable with an active electronic component within the structure. This method applies to relatively thin sensors and has not been explored to create larger structures.

2.3 Dual Material 3d Printing

FDM dual material printing allows you to print parts with two different materials using a single extruder or dual extruder heads. Each head can dispense a different type of material. The two materials can be different colors or have different mechanical properties, such as hardness or flexibility. To print with two materials, the printer uses a technique called "dual extrusion." This involves printing with one material until a certain height is reached, then switching to the other material to continue printing. The process repeats until the part is complete. Dual material printing allows for more complex and functional designs, as it enables the creation of parts with different properties in different areas. For example, you can print a part with a hard outer shell and a flexible inner core, or a part with a different color on the outside than the inside. Some common applications of FDM dual material printing include prototyping, product design, and small-scale production. However, it is important to note that dual material printing can be more challenging than printing with a single material. The materials having different melting temperatures can cause uneven cooling resulting in parts to unstick from the bed or poor adhesin between different material layers. A study done by Kim et al. [3] tested samples using ABS and PLA filaments using FDM. They created dog bone tensile test samples that were made of different percentage of PLA to ABS as shown in the figure below.

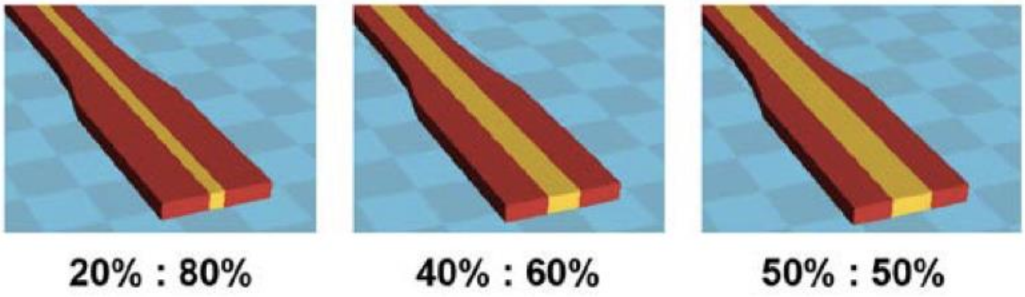


Figure 1: ABS PLA dog bone specimen [3]

They explained the results of these dual materials did not have a great significant difference of tensile strength of the specimens unlike the pure PLA and ABS samples. They also noticed that fractures were found at the interface of the two materials. This is the result of different shrinkage rate of the two materials as ABS due to its higher melting temperature can shrink by up to 8% compared to PLA's 2%. Kim explained FDM demonstrated unstable extrusion that created voids and overlaps at the boundary layers between the two materials.

In another study done by Taebnia et al. [4], SLA was used to create a model to mimic the small intestine. To accomplish the two material prints to resemble the intestine, they switched the resin vats containing two different materials. This creates a layer in which separates the two different materials. Using this method to create dual material parts can limits the ability to create a structure with a harden core with a soft outer shell as the print is already half printed when the other material is introduced.

As of this study, there are no indications of dual material hybrid printing using DIW and VAM. With this new look on combining these two-technology inspiration can be given to explore other hybrid methods of printing that can enhance the 3d printing.

2.4 Researching Parameters

2.4.1 Resin:

The most important part of modern SLA and DLP 3D printers is the photosensitive resin used to create the hardened 3D structures. Coming in multiple colors the uncured commercial resin consists of 4 main parts: monomers, oligomers (3 or 4 monomers already stuck together), photo-initiators, and UV- blockers. The curing of the resin begins when a concentration of blue UV-light interacts with the molecules starting a chemical reaction that bonds the monomers and oligomers together. During this process, the UV-blockers stop the blue light from penetrating too far into the resin and solidifying parts of the structure that should not be solidified, allowing for fine detailed structures. With enough concentrated Blue UV-light, a structure begins to form.

As the resin cures, it tends to stick to whatever base its cured on. Modern printers use silicon or techniques such as sliding and lifting the structure off the base to deter a suction force that would rip apart the cured resin. Due to silicones permeability with oxygen, it creates a miniscule layer between it and the resin that stops the resin from sticking. With the volumetric 3D printer none of these typical methods will be needed to stop the resin from sticking. With the viscosity of the resin the created part can float in the middle of the resin, not having to touch the glass cup it is made in.

Typically, modern printers use orange plastic to encase the resin which stops unexpected curing from outside UV-light. Since the resin only cures from blue UV-light, the orange plastic will transform outside blue light into green light that does not cure the resin [5].

After curing, structures are sprayed with alcohol remove any excess uncured resin and then moved into post curing which solidifies the structure. The remaining uncured resin can be drained and used for future projects. Aside from average uses most 3D printers share, this form of additive manufacturing is especially helpful for biomechanical and medical usage. Since the structures are only touched by the UV-light they remain sterile during their creation. With the speed of an all-at-once printer, specific detailed medical tools, optical assortments, and typical use structures can be fabricated in only minutes.

2.4.2 Radon/Reverse CT Scanning to Image Processing:

The Volumetric 3D printing process is unlike any traditional DIW printing and, as such, conventional slicing techniques for processing a 3D file is unconventional. Rather than building the part out of a series of layers in the Z-axis, instead the part is built from a series of axial slices projected onto a resin container rotating. The biggest challenge in printing an object using volumetric techniques is the coupling of resin hardening with image processing techniques. As seen in Figure 2, volumetric printing has found a theoretical object solidification technique using light patterns cast onto a vat of photosensitive resin. The ability to control the light intensity of the projected image is crucial in accurately printing an object.

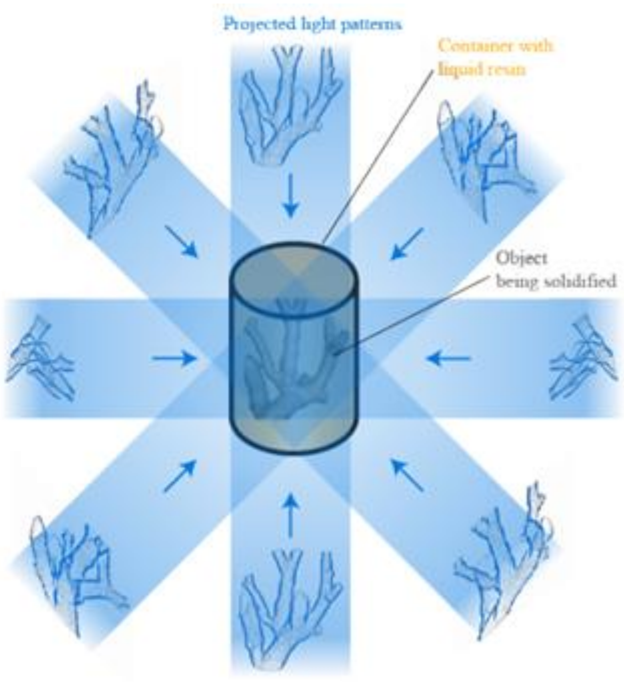


Figure 2: Theoretical Volumetric Printing Technique [1]

Of the few volumetric printers available today, a large majority of these printers utilize a reverse computed tomography algorithm in which a series of 2D images is created by rotating a part about some axis and then these images are projected onto a rotating resin vat. One such example that is well documented is the algorithm described by Kelly et. al. [1]. Using their so-called CAL algorithm, Kelly uses a physical implementation of the back-projection algorithm used in CT reconstruction. Using STL files, a voxel image is described for a z-slice of the target geometry using three equations. Firstly, Eq 1 describes the printed geometry using back-projection which accepts a value of 0 or 1 representing the presence or absence of material where I is an indicator function expressing the threshold, D_c is the critical dose that defines adequate solidification of the material, α is the resin's optical absorption coefficient, and $\boldsymbol{\Omega}$ is the rotation rate of the container.

$$\begin{aligned} f(\mathbf{r},z) &= I\left\{\frac{\alpha}{\Omega}\left(T_{-\alpha}^{*}[g](\mathbf{r},z)\right) \geq D_c\right\} \\ &= I\left\{\frac{\alpha}{\Omega}\left(\int_{\theta=0}^{2\pi} g\left(\mathbf{r}.\hat{\theta},\theta,z\right)e^{-\alpha\mathbf{r}.\hat{\theta}_{\perp}}\,d\theta\right) \geq D_c\right\} \end{aligned} \tag{1}$$

Then, Eq 2 describes the formulation of the optimal incoherent intensity projections solved by the three-dimensional inverse problem where, $g_{opt} \geq 0$ and f_T are the back-projection algorithm for the target geometry.

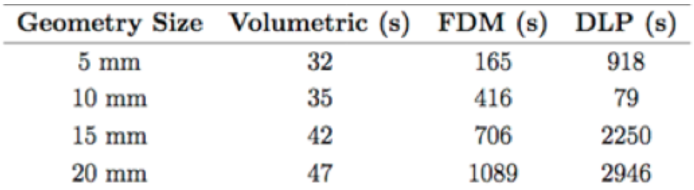
$$g_{opt}\left(r,\theta,z\right) = \operatorname{argmin} \| f - f_T \|_2 \tag{2}$$

Other techniques not described in [1] are also used to optimize the projections to create sharper images using filtering techniques. Other entities such as Vidler have considered options of the same back-projection algorithm. Vidler considers a single two-dimensional slice of the object denoted by δz, which represents the cross-sectional view of the object at a given z increment. For this slice, volume is represented by the presence of a '1', with the absence of material represented as a '0'. Now for each planar angle θ through this volume the radon transform is computed which represents the line integral through the volume at the representative angle θ [1]. Equation 3 is the two-dimensional Fourier transform, and cannot be used as is, because of the inherent limitation of probing for infinite points in an object. Therefore, interpolation along these radial lines onto a uniform grid using nearest neighbor or linear interpolation techniques can then be used to approximate the missing data from the two-dimensional Fourier domain.

$$F(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)e^{-j2\pi(ux+vy)}dxdy \tag{3}$$

Vidler notes that of the there is greater error in representing higher frequencies (sharper features) of the object compared to the lower frequencies. For the two dose distribution techniques using back-projections above have both been proved capable of creating images for use in volumetric printing using photosensitive resin. Vidler conducted an extensive study on the quality, effects, materials, and lighting that should be used in volumetric printing among other things to surpass the quality and speed of layered 3D printing. The results of the print times (see Table 1) are a compelling reason for the continuation of studies and testing of this process. Mentioned on page 72 of Vidler's study, the mechanical strength of the volumetrically formed solid was also tested and then compared to that of a cast molded solid. The results of the volumetrically printed objects are comparable in strength to pristine molded samples, which could easily surpass the strength of any layered resin 3D printed object.

Table 1: Results for the investigation of print times for common additive manufacturing methods [1]



Geometry Size	Volumetric (s)	FDM (s)	DLP (s)
5 mm	32	165	918
10 mm	35	416	79
15 mm	42	706	2250
20 mm	47	1089	2946

2.4.3 Noteworthy Issues/Limitations

As noted by Vidler [1], using low viscosity resins can cause printing errors when the resin starts to solidify due to density changes and sinking, resulting in a skewed version of the intended shape. It is also noted in the research that the minimum viscosity needed can be calculated or the use of a material that has little to no difference in density when in its liquid and solid states can prevent this from being a problem [1]. Another issue that was brought up during Vidler's research was the light concentration/exposure differences between inner and outer radial sections of the printed object. Because the projection will rotate about the vertical axis, the parts with the largest radial distance will end up “experiencing a lower cumulative dose” of light than the inner parts [1]. To sufficiently solidify the outer sections without overexposing the inner sections, equipment capable of projecting different levels of light concentration simultaneously could be useful, if not essential, for the printing of certain shapes and objects.

CHAPTER THREE: METHODOLOGY

3.1 Methodology parameters

Before setting up the hybrid system, certain parameters need to be evaluated to be able to pick out the best equipment and techniques to achieve an optimal base for the system. This chapter will cover the principles of the system and the iterations that were created with the sources we gathered and developed.

3.1.1 Projection Technology

All image projection technology (computers, TVs, projectors, etc.) use 3 colors: red, green, and blue. Essentially all colors that are seen by the human eye are a mixture of these three colors in different proportions (Figure 4) [6]. There are 3 different light sources available for projectors: bulbs, light-emitting diode (LED), and laser. This section will assess the efficiency, lifespan, light paths and size as well as comparing general pros and cons for each type of projector light source. In projectors that use single chips, the assorted colors of an image are not projected simultaneously but consecutively. They are constantly switching between the red, green, and blue portions of the images at a higher frequency, and the different color images mix to show the resulting colors [6]. This is not necessary for multi-chip projectors as each chip will project only one of the 3 primary colors.

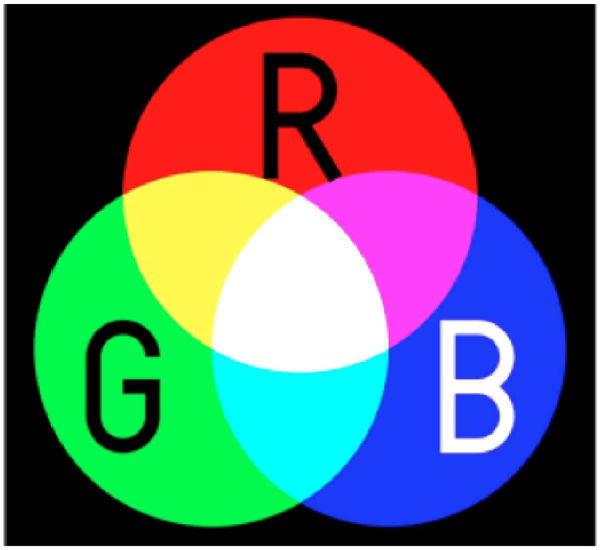


Figure 3: Primary Colors [6]

3.1.2 Light Path and Size

Different kinds of light sources require different kinds of light paths. A light path being how the light is filtered/separated into red, green, and blue (RGB) light. As shown in Figures 5A and B below, lamps will start with the white light and use either a filter (aka color wheel) for a single chip projector or dichroic mirrors for multi-chip projectors to create the different colors. Dichroic mirrors reflect a certain range of wavelengths and allow the rest to pass.

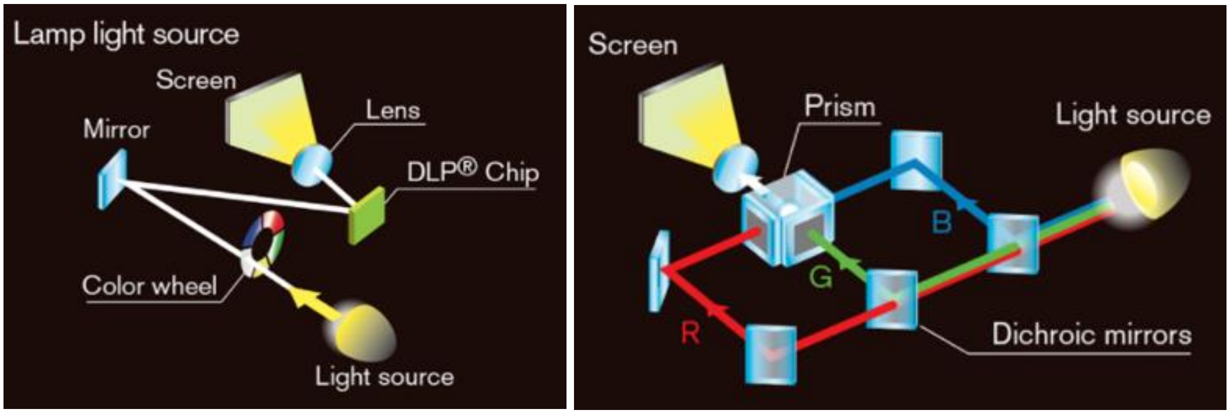


Figure 4: Light path of single chip and multi-chip bulb projectors respectively [6]

Laser projectors have multiple options as well. Single laser, or blue laser, light source projectors use phosphor wheels to separate the blue from the red and green wavelengths (combined show as yellow), then go through a series of mirrors, lenses, and a color wheel before reaching the DLP chip (see Figure 6A). Much like with the multi-chip lamp projector, dichroic mirrors can also be used in single laser, multi-chip projectors. There are many ways to set up projectors using multiple light sources (excluding bulbs) with one or more chips. There are projectors that use red, green, and blue lasers with either one or multiple chips (Figure 6B), even some that use blue lasers and red LEDs (Figure 7). As expected, the higher the number of light sources and chips that are used in a projector, the “purer” the results and the bigger/more expensive the commercial projectors will be.

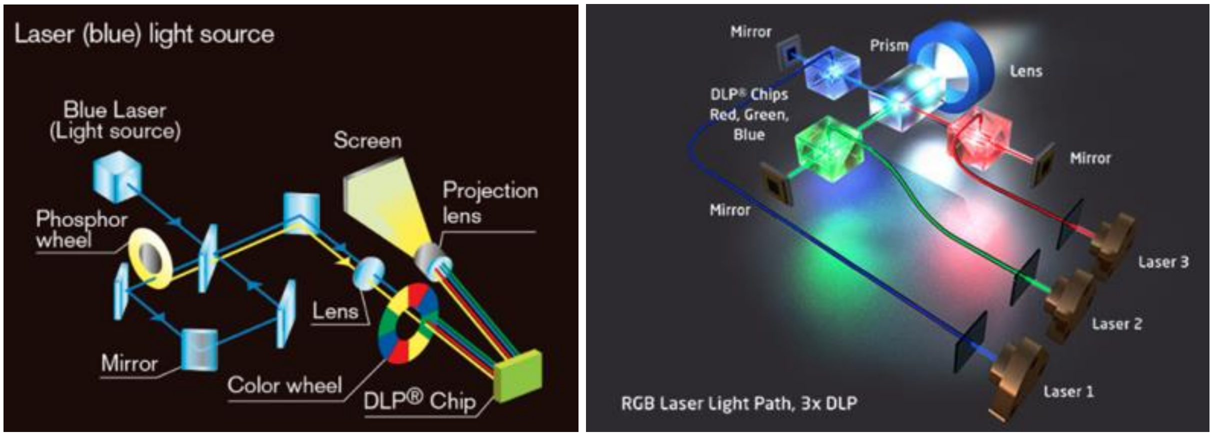


Figure 5: Blue laser, single-chip projector [6] and multi-laser, multi-projector light paths [7]

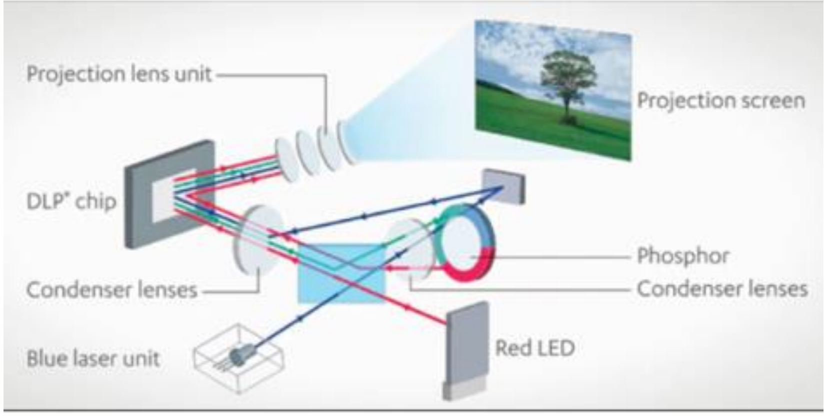


Figure 6: Blue laser and Red LED, single chip projector light path [6]

Because LEDs are small in nature and can turn on and off at a high frequency, the projectors can use one chip or multiple, with no need for filters or elaborate mazes of mirrors. They also do not need a fan for cooling because they do not get very hot. As a result, most small projectors use LED light sources. However, there is a tradeoff between the size of a projector and the level of power/brightness produced.

3.1.3 Efficiency

Projectors use different types of light sources and have a relatively narrow range of red, green, and blue wavelengths. Below are images of the wavelengths emitted by each light source to better compare them.

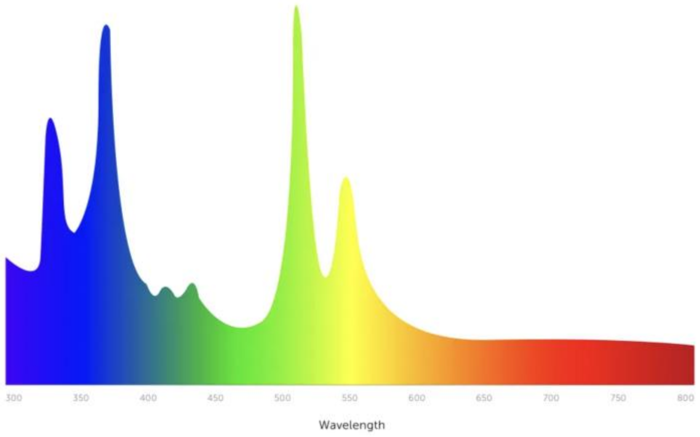


Figure 7: UHP Lamp (bulb) Spectrum [8]

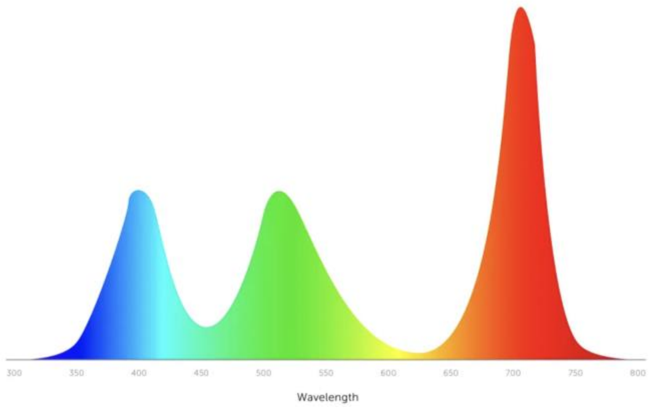


Figure 8: LED Spectrum [8]

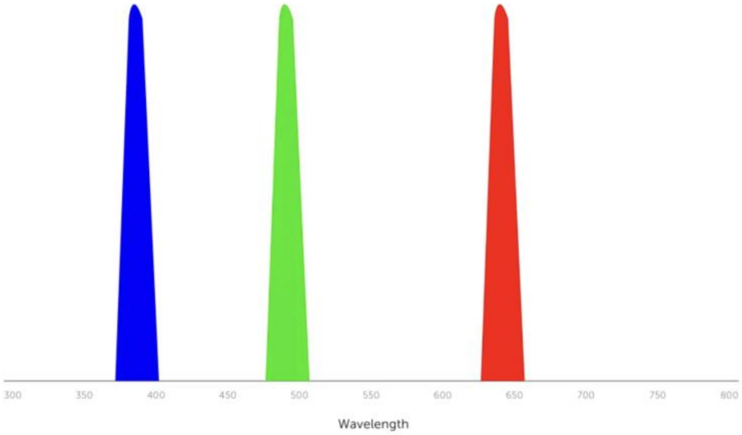


Figure 9: RGB Laser Spectrum [8]

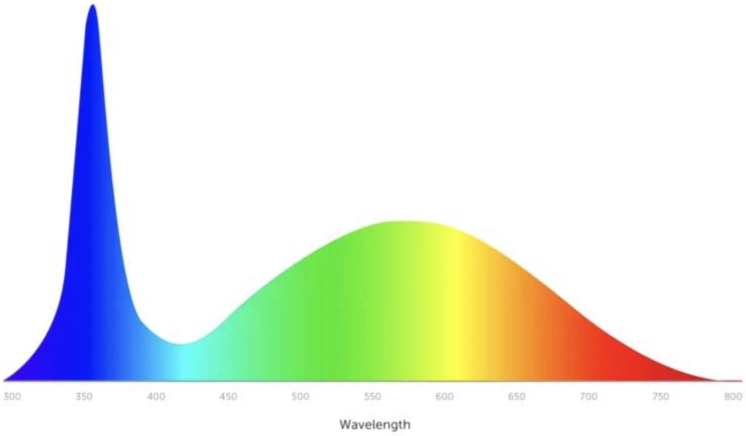


Figure 10: Laser Phosphor Spectrum [8]

As seen above, the bulbs wasting a lot of power emitting wavelengths of color that will not be utilized by the projectors. LEDs are slightly more efficient as most of their power output is used in red, green, and blue wavelengths. RGB Laser projectors (unlike laser phosphor projectors) are highly efficient, using all their power to produce narrow ranges of red, green and blue wavelengths. [8]

3.1.4 Lifespan and Brightness

Table 2: Lifespan and Brightness Comparison

Light source	Lifespan hours	Brightness (Lumens)
Bulb	2,000-10,000	1,000-43,000
LED	+20,000	10-4,500
Laser	+20,000	32-75,000

What is not shown in the table above is that bulb lamps lose brightness at a much quicker rate than LEDs or lasers. The brightness of a lamp can drop up to 25% within the first 500 hours then gradually drops to 50% (defined end of life). This means that even though the bulb still works, the brightness at the end of its "lifespan" will be less than 50%. The solid-state projectors (LED and lasers) have a linear loss of brightness over their lifespan and take much longer for any initial loss of brightness. Some LED and lamp projectors also use "white light" to increase brightness of images, often resulting in a loss of color accuracy. That is, on the color wheels they will have a clear panel for white light which will decrease the use of color light resulting in "faded" colors. [6]

3.1.5 Resin

The material used in the design of a new VAM, understanding the properties of the resin that are displayed after the stereolithography process occurs is important. These properties are, as stated in the American Chemical Society: “high cross-link densities result in increased stiffness and high thermal stability, whereas toughness decreases. Indeed, despite their rapid curing and good spatial resolution, acrylate systems commonly show low toughness and tend to be brittle” [9]. Other properties include, “low shrinkage, excellent adhesion to various substrates, effective electrical insulation, chemical and solvent resistance, and a low cost [10].

3.1.6 How Resin Reacts with Light/What Types of Light

As defined in the previous section, epoxy resins and acrylate resins are thermosets. The definition of a thermoset is that it is a polymer, whether liquid or powder, that will harden and cure when heated, treated with chemicals, given pressure, or undergoing radiation. The method by which VAM will be curing the resin is through UV radiation. When UV light cures the resin, the specific wavelengths of UV light interact with the photo initiator molecules, transforming them into molecules that now can bond separately from the monomers and oligomers, eventually developing into polymers [11]. In the process of the polymers forming, the liquid resin transitions into a solid resin structure.

3.1.7 Factors/Concerns to Consider

Another factor of this topic is the importance of the UV light in the process of printing, specifically with the container that holds the resin during printing process. A tank or vial will be used for the resin that will be held and upright as opposed to normal SLA printers that have a basin for their resin along with an elevator to raise and lower the material. When choosing the container for the resin, the specific needs of the printer must be kept in mind, namely that it is able to withstand UV radiation (glass or plexiglass may be needed), and that it is a material that will not allow for any resin residue to stay on its surface (for efficiency and reusability purposes, as well as to prevent any refraction of the UV projections into the resin).

Another concern is the presence of bubbles in the liquid resin that occur when using resin as instructed (shake thoroughly). One paper by Vidler [1] displayed a method of removing the bubbles from within the mixture by heating the resin up to a temperature of 70°C and then slowly mixing the two-part resin together and finally vacuum sealing the resin. He continued and discussed a process in which the photo initiator mixture was put into a hot water bath to decrease the viscosity and then mixed isopropanol in a 1:1 ratio. The mixture was then vortexed and left to sit in the water bath until the photo initiator was fully dissolved. This means that care should be taken to remove all bubbles and precautions should be taken to reduce the amount of movement that is translated into the resin in this design. The more movement that occurs and the more air bubbles that remain in the mixture will mean more potential to ruin the print.

3.1.8 Motor Types

First to be discussed: the motor depicted in the project description; a belt driven motor. It utilizes a rotation device attached to a pulley that would spin the platform housing the projectors. Then there is a direct drive motor, which seamlessly connects the platform to the motor. Finally, there is a stepper motor, a type of direct drive motor that rotates in increments, or steps, which can be controlled.

For a project potentially on a tight budget, belt driven systems seem to be ideal; “belt driven rotary tables generally offer the advantages of high speed and low cost in rotary positioning applications” [12]. This system for platform rotation is a simple yet effective solution, not requiring much in terms of money, maintenance or expertise. But it may come with significant drawbacks, most notably, from the belt itself. The material of most belts used in any type of belt driven motor system promotes wear and tear and ultimately would not be useful for long-term application. It is reiterated that “due to the potential for elongation of the belt, positioning accuracy of belt drives is often inferior to other alternatives” [13] although that is not to say a prototype couldn’t benefit from a system such as this.

Direct drive motors as stated before would rotate the platform and load directly through contact. This may eliminate some problems that arise with belt driven motors, “direct drive systems generate energy savings by operating at high levels of efficiency because the elimination of the power transmission system provides a substantial reduction in friction. Direct drive systems also have fewer components, which often reduces maintenance requirements and provides quieter operation because there are fewer parts that can vibrate” [12]. This kind of system, however, would generally be more expensive than its pulley counterpart. It is worth mentioning that this kind of motor system can provide higher levels of precision regarding its rotation speed, vibration feedback, and stiffness. Considering the size and load capacity for this project, it would seem most feasible to use a direct drive motor should the budget allow it, albeit for a late-stage model, most likely something closer to completion and less of a prototype.

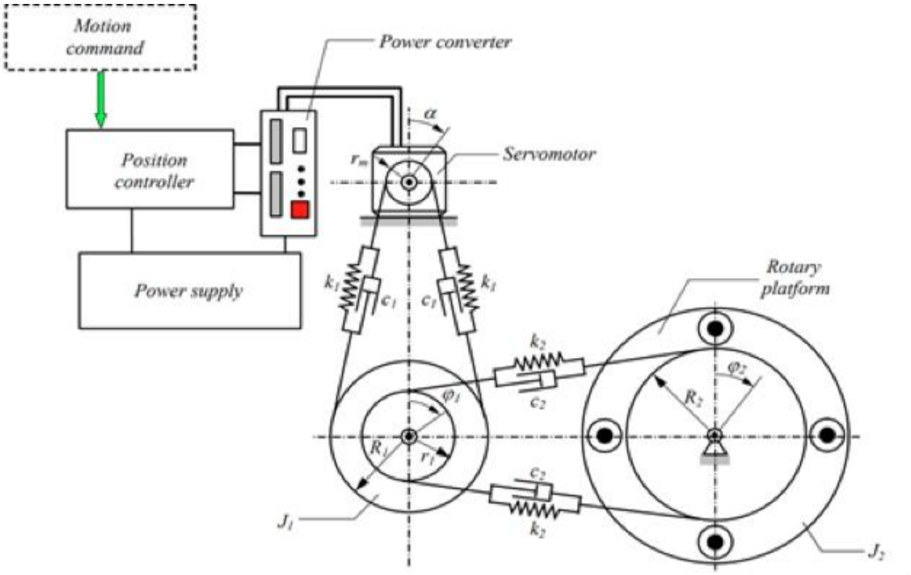


Figure 11: Rotary platform driven by a servomotor through a two-stage belt transmission [14]

For an added element of precision and control a stepper motor is yet another option for controlling the rotation of the projector. The stepper motor would rotate the platform at predetermined angles allowing for a very precise speed of rotation affecting the customization of the printing settings. “The stepper system of a rotary table consists of two complementary components: the stepper motor and stepper drive. The stepper drive works alongside the step motor to enable rotations of the rotary table in pre-defined angles” [13]. Precision can be achieved with a stepper motor using an open loop control system, whereas many other motor types require closed loop systems in order to be precise motion controllers.

3.1.9 Vibrations

An important design goal in this project is to reduce the overall vibration of the system to avoid disrupting the resin during the print curing process. Depending on the rotation mechanism vibration can be mitigated or worsened. To see how this works, comparisons to different mechanical applications of these types of rotary systems will be made.

To start, a similar design to the rotation projectors would be that of a turntable, the drive motor acting in the same manner and the turntable holding the platter substituting what would be the platform housing the projectors, “the elastic belt soaks up shock and prevents vibrations that are produced by the motor from catching the platter” [15]. Another direct comparison could be to that of a washing machine, again the motor and belt working relatively the same, and the wash drum acting as the platform and the projectors. Here again it is seen “when using a belt, it acts as a shock absorber, the tank, in turn, also has shock absorbers” [16].

Figure 12: Belt driven motor vs direct drive motor in washing machine systems [16]

There are many aspects to consider for the rotation device controlling the projectors. Ideal aspects are cheap, reliable components that are easy to procure and use and do not interfere with the printing process by means of excess vibration or movement. Of course, an ideal product is less than feasible but with proper management and decision-making necessary sacrifices can be made in the fields that a lot them to ensure a well working manufacturable machine.

3.2 First Step Concept

Initially, the first prototype involved developing the critical systems to their barebones. The key systems concepts needed to be tested were the resin hardening, DLP projector, a motor to rotate a small resin vat, and an initial algorithm controlling the projected images. Seen in figure 7.7, the initial prototype featured a rudimentary frame constructed from 20x20 mm T-slots with a simple DC motor spinning the resin vat powered by a DC bench power supply. These first tests using this prototype were conducted to correctly identify how our system would work, and how the system responded outside of theory.

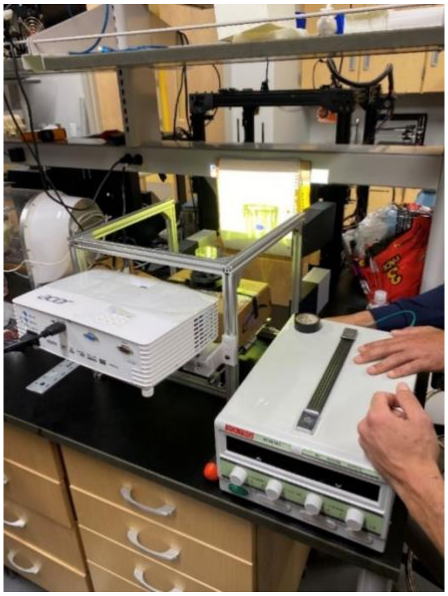


Figure 13: Initial Resin Printing Prototype

Initial attempts showed promising results with rudimentary shapes, see figure 7.8. With this, we were able to identify key systems that failed. For example, the first photosensitive resin that was used had many issues with floating parts, and with this information we were able to identify resin with different liquid properties to minimize this issue.

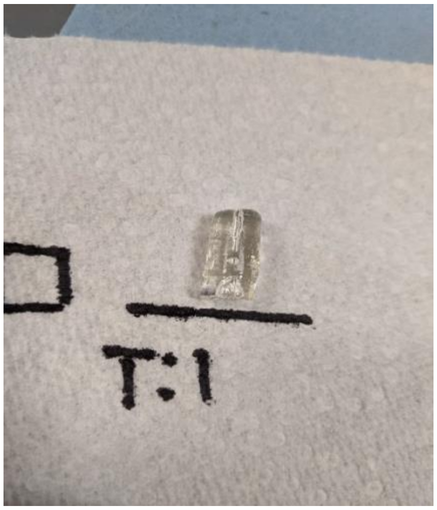


Figure 14: First Successful Print

The first prototype of the resin hardening projection algorithm consisted of using differences in wavelength, i.e., different colors to control the areas of the resin vat that will and will not be hardened. Figure 7.9 shows an example of the projected image that will print a 3D object. Note that all parts printed using this algorithm relies on an image having rotational symmetry, which is when two of the three axes' projections have the same principal axis. In this figure, the projected image of a rectangle results in a cylinder being printed. When the image is projected to the resin vat, the areas which harden the resin use a wavelength of 405mn, standard for off the shelf photosensitive resin, while all areas which are not wanted to be printed are in a wavelength of around 200nm higher, in this case, 405nm corresponds will purple, while the non-printed area corresponds with yellow.

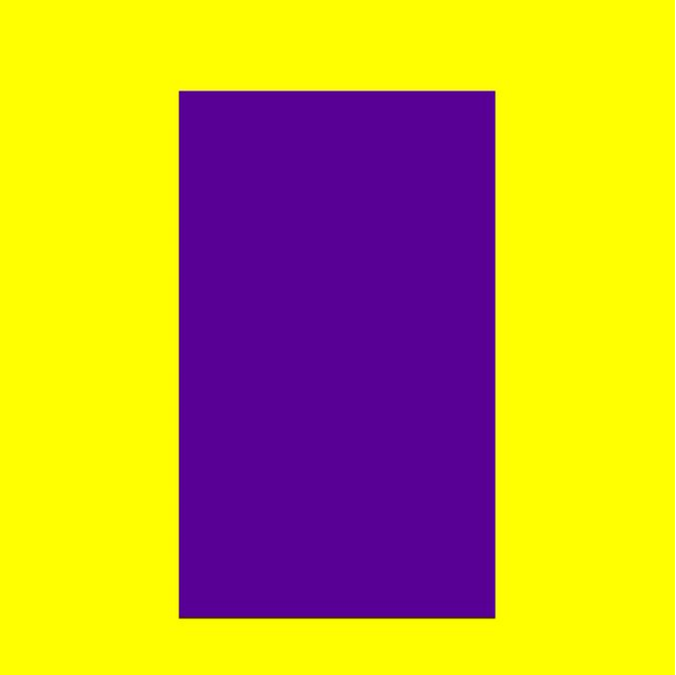


Figure 15: Resin Hardening Projection

3.2.1 First Step Concept Design

The final design of the first VAM system can be seen in figures 16 and 17. This design relies on an old Photo-elastic Measurement Device seen in figure 18 that was repurposed for the printer. With this, manufacturing was kept at a minimum; most manufacturing consisted of drilling and tapping mounting holes and 3D printing parts. This old Photo-elastic Measurement Device was used instead of the originally planned t-slot frame due to this object being provided and was useful for reducing vibration transfer from table to resin vat that could ruin the print. The entire profile of the printer contains a 22 in wide, 5in tall, 49in long bottom housing which the build tower is mounted to. Contained in the build tower are two lead screw motors mounted in parallel to control the build volume's vertical position. In future iterations, this will be used more to print larger parts. Using this repurposed measurement device, the durability of the hardware supporting the system greatly increases from the t-slot prototype.

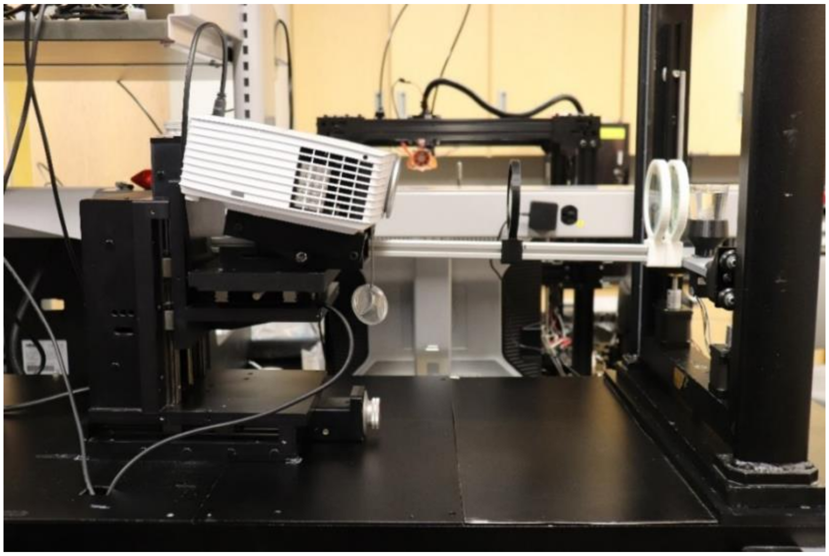


Figure 16: Final Projector Design

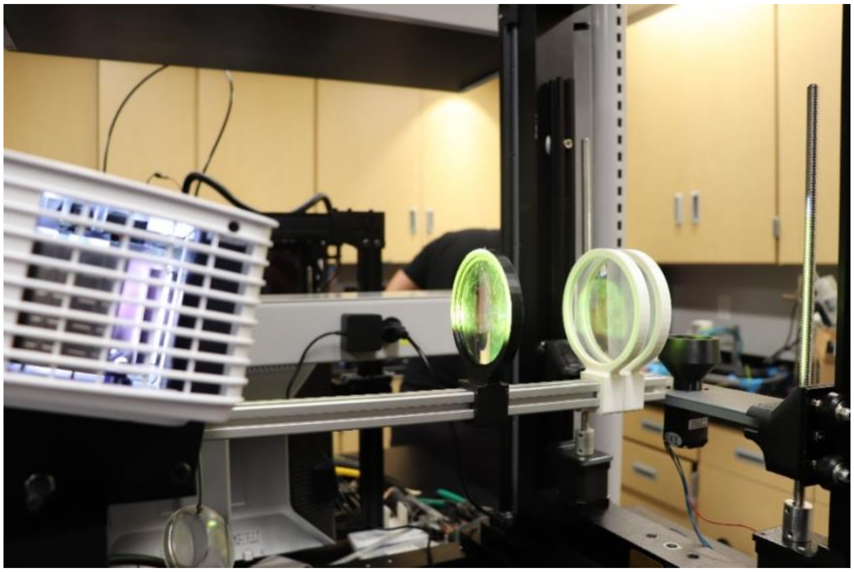


Figure 17: Final Projector Design

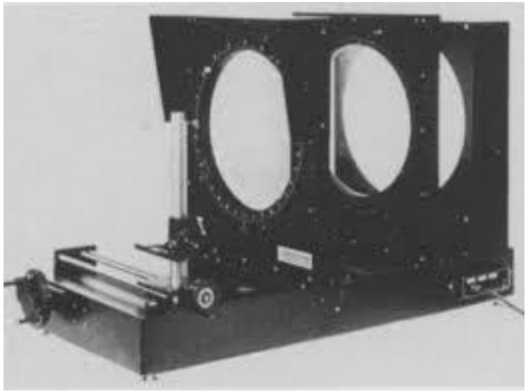


Figure 18: Photo-elastic Measurement Device [6]

In figure 16, the projector can be seen sitting on a linkage system that controls the angle of projection of the printer. Using this linkage system, figure 19, the angle of the image projected is controllable to align the image into the resin vat. The mounted projector sits on a 3-axis adjustable mount to further increase the alignment of the projector image with resin vat.

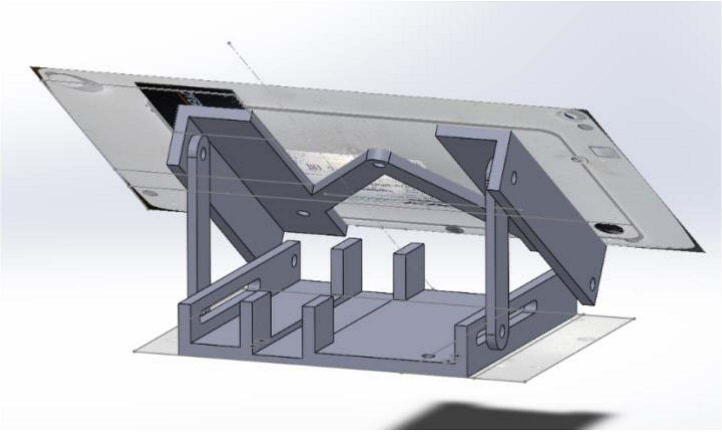


Figure 19: Angle Adjustable Linkage System

The lens setup in the middle of the projector, seen in figure 20, takes the energy from the projector and increases the amount of energy per square millimeter to further reduce printing times.

This is done by taking what would normally be a diverging projection image and converging the light into the resin vat.

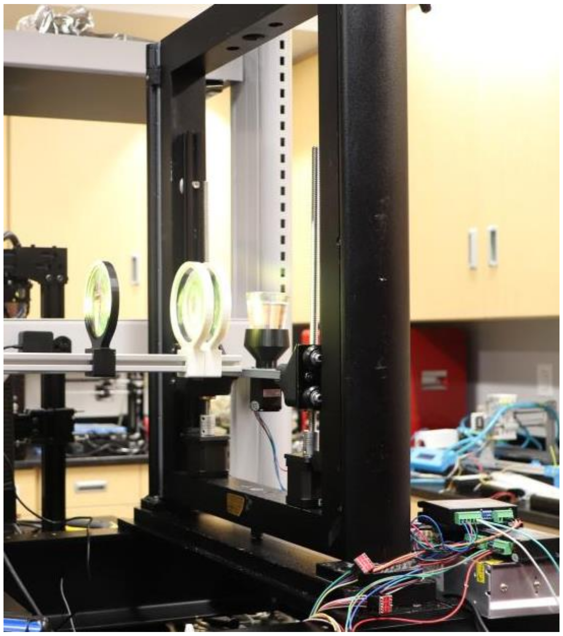


Figure 20: Resin Vat

The choice of lens in this area of the printer was done to correctly control the light used for printing. By default, the light particles diverge once leaving the projector. To completely harness the energy output from the printer, we chose to converge the light, as seen in figure 21. Adding the parameter of lens into the printer, another challenge arose in part printing. While the energy per square millimeter rose, and ultimately the print times decreased. Due to the nature of converging light, prints became warped due to the unevenness of light particles. Because of this, three biconvex lenses of two times magnification were chosen and arranged in order to condense the energy while keeping converging light particles at a low convergence angle. By doing so, this was useful in reducing prints floating out of place in the resin vat. The resin vat mounts a glass directly to a stepper motor to rotate the resin vat at speed of 60 degrees per second. Powering the entire printer is the circuit, which can be seen in figure 22:

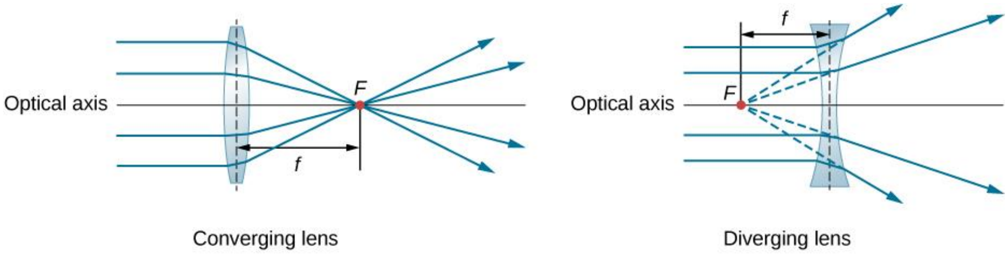


Figure 21: Converging and Diverging Light [17]

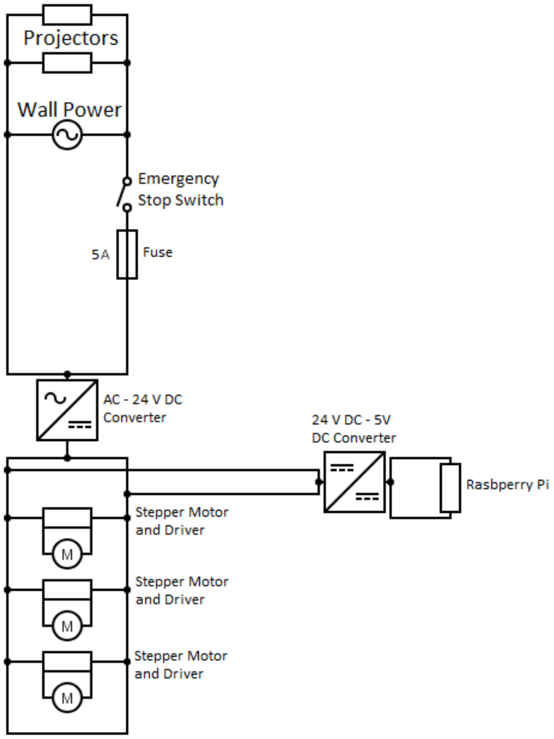


Figure 22: Power Circuit for Printer

The final projection algorithm used on the projector was a forked version of the prototype projection algorithm used. Still using parts that are rotationally symmetric, final software control has support for any complex shape by using a triangulation method, an array of vertex points for any arbitrary shape is passed into the code. Additionally, this program that projects the image controls the rotation speed of the resin vat.

3.2.2 Open Issues on First Concept

The mounting plates for the projector reached a desired modular setup that allows for the projector to be adjusted to varying degrees of inclination. This was a huge success from the initial design that was static and nonmodular limiting the degrees of freedom. With the addition of a proper projector mounting plate, calibrating the setup with the focusing lenses was more effective and efficient. Along with the rest of the platform, our objectives were met to create an initial prototype that prints a desired part with an acceptable degree of precision. Uncertainties arose with the lenses used as they were of unspecified focal lengths which made finding the proper setup with equations difficult enough that the focusing of the image was done manually. There is a lot more research that needs to be done on lens physics and how the energy of the UV light is affected when shot through lenses in series. There were chromatic aberrations in the projected image as the light was shot through the lens series that caused warping and increased the difficulty of calibrating the setup. Using a projector to passively project an image onto the resin does not have the desired ability to modify the amount of UV light being exposed to precise areas that need to be cured. It would be more advantageous to use lasers that are collimated through aspheric lenses in order to control the amount of divergence from the light ray as it reaches the print volume. Another drawback that affected the printing process was that the piece being printed would begin to float to the top of the resin vat before finishing, disfiguring the desired outcome.

Figure 23: First Iteration Prints

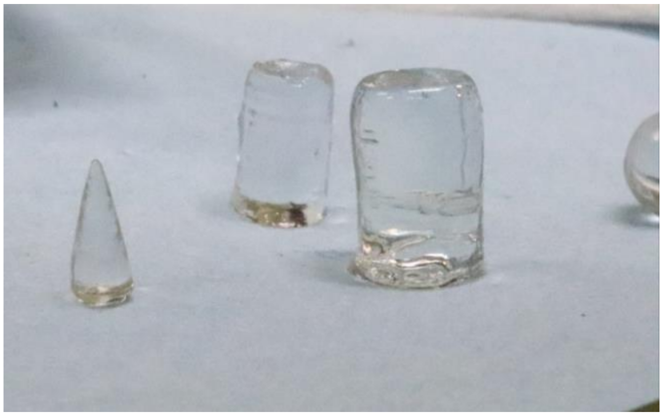


Figure 24: Cylinder and Cone

Figure 25: Pawn chess piece

3.3 Second Step Concept

Once the first step of the concept was achieved, the next milestone was to maintain print size with a smaller projector and create more complex prints while maintaining same print quality by using multiple projectors rotating around the resin. In the first concept design the resin vat was rotated which would lead to centripetal forces acting on the part. Using this DLP technology requires simultaneously controlling the light and lenses of all the projectors to focus the UV light to the specific wavelength and intensity for the resin to cure (i.e., photocuring) in the location of the images also while using tools like volumetric rendering to project and print a large-scale or complex 3D image. The challenge with regular projectors is the lack of high-power density light needed for photocuring the resin due to the masking medium of regular projectors. Photocuring in this instance requires the use of specific lenses like a fresnel lens and light diffracting prisms [1]. Also, another challenge would be calibrating the system to have the right wavelength only at intersecting points in the resin as well as accounting for the light refraction of the light-permeable container. Figure 26 below provides a conceptual idea of how one of these 3D printing systems would work.

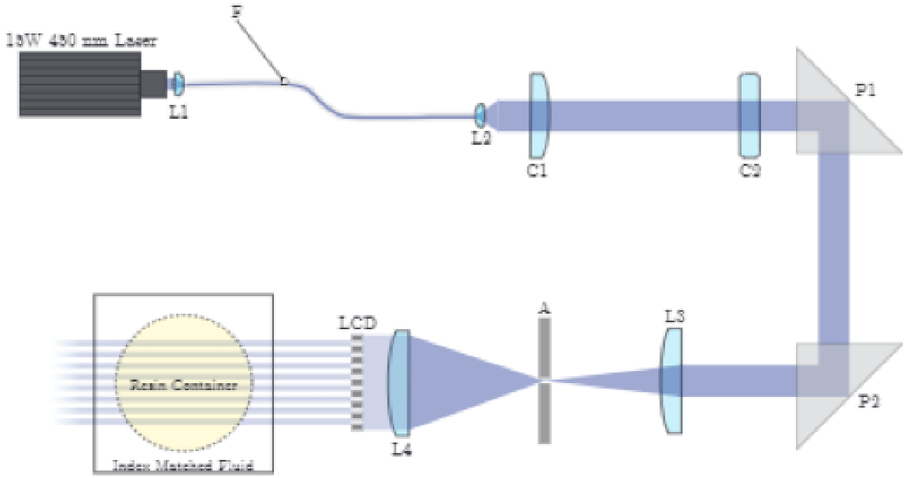


Figure 26: The optical layout of a DLP system [1]

3.3.1 Second Step Design Concept

The key function of this step is the rotation of the platform that would rotate at least one projector (if not more) around a central axis located around the resin vat to produce consistently adequate prints and the projection of UV light into the resin vat that will trigger curing of the desired object.

During testing of the previous design, it was believed that rotating the build tank produced more volatile and inconsistent prints in the resin medium. Rotating the projectors was determined to be the next step in trying to alleviate this issue in the current design iteration. A critical feature that will allow for smooth operation is a cable management system that prevents cord tangling and coiling during operation, as this issue would prevent the printer from performing as intended. The location and orientation of the projector as well as the complexity of the light delivery system may dictate where the cables will feed into the machine, and subsequently dictate the geometry of the cable management solution. Without originally knowing the size or configuration of critical components that would be used in the system, it was impossible to determine the location or orientation of the wires. Regardless of what the geometric solution is, a power source or connection with the ability to repeatedly rotate 360 degrees must be utilized to prevent twisting/tangling of the cables while the projectors are rotating.

Since one of the goals was to print objects in a relatively short print time, a larger concentration of UV energy would be required. This means that the projector output must increase. The rotating base/platform must be stiff enough to support the weight of the UV projection systems being implemented, meaning a higher density/thickness of material may be necessary for critical support locations. This would result in an increase of overall mass. In addition to mass, the shape and dimensions are important factors to consider when trying to minimize the rotational moment of inertia to minimize the torque requirements of the main rotational motor. Whether the projector would be oriented vertically, horizontally or tilted at an angle is dependent on the projector's size, power source location and the projection output angle.

A projector rotation system for the second iteration is one of the key goals of the design. The rotary system must rotate and support two projectors of unknown size in an untangled, steady rotation that does not cause vibrations to occur that would disrupt the print. The biggest issue initially was to create stable rotation. It was necessary to determine what the structural and mechanical qualities of the system would be to accomplish this. This is where the resin and projectors had a large portion of consideration when coming up with concepts, but since it was originally decided that the design would utilize three projectors and commercial resin, these two considerations were generalized to make things simpler. When it became time to generate a prototype for experimentation, these two components were given more attention.

The force required to turn 2 projectors has been an important topic of project discussion. The weight of the projectors plays heavily into the decision-making process in this aspect of the design, as a result, the design's dimensions were based on anticipated load demands. However, in the current iteration of the design, concepts have been developed in order to overcome the weight problem through design, modification and thickness of the turntable. One design had projectors pointing the bulbs upward to decrease the moment of inertia of the turntable (Figure 27). Another solution was to make the shape of the turntable into a three-winged platform (Figure 27), eliminating excess material mass that would not be used for staging. Other designs have implemented mirrors to reflect the projection onto the vat that would be high above the spinning platform to reduce vibration.

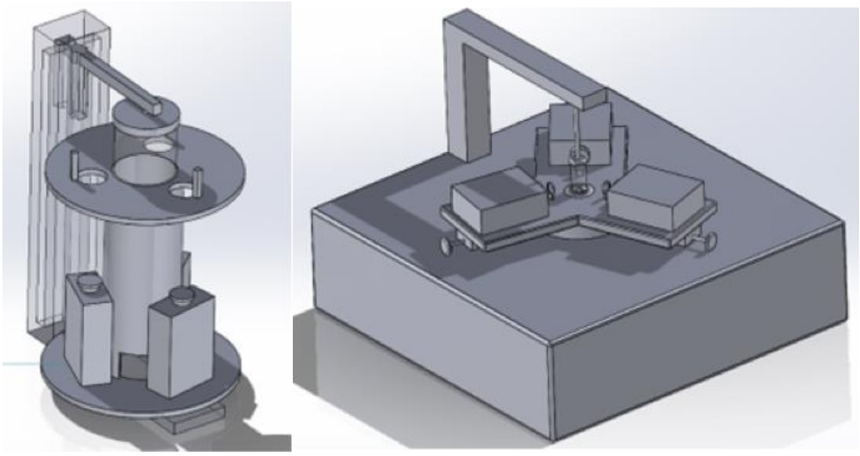


Figure 27: Upright projectors and Winged turntable designs

One of the main problems that needs to be addressed in the design is cable management. For the projectors to remain on and stable during a print, an efficient method of rotating the wires or power source is needed to prevent wrapping and entanglement. Theoretical solutions are currently based on socket plugs that can rotate 360°, which could allow the projector power cords to simple be fed through the middle of the platform into the rotating plug/splitter, giving all the wires the ability to spin in tandem without being tangled.

One other consideration was considered for system concepts, the optical assembly. The solution implemented by Vidler in his experimentation was to immerse the vial in a rectangular tank of refractive index matched fluid [1]. While his experiment also utilized only one projector, the original concept for this iteration would need to utilize a triangular prism tank that would move in conjunction with the rotating platform and be oriented so that each face of the prism is perpendicular to its respective projection light path. It was the hope that this would reduce the amount of light refraction.

Another factor that was to be considered in the actual rotation mechanism was how to ensure smooth rotation that would produce minimal vibrations and prevent any disruption that may reduce the fidelity of the print. One of the possible solutions discussed was to build a turntable utilizing ball bearings that would allow the rotating platform to be driven by the transmission of rotary motion from a wheel powered by a single motor. This idea would help simplify and decrease the amount of space required for the subsystem as well as the overall design. It would also increase flexibility and reduce costs by utilizing commercially available components unlike other options such as constructing gears and belts that would possibly need to be customized (Figures 28).

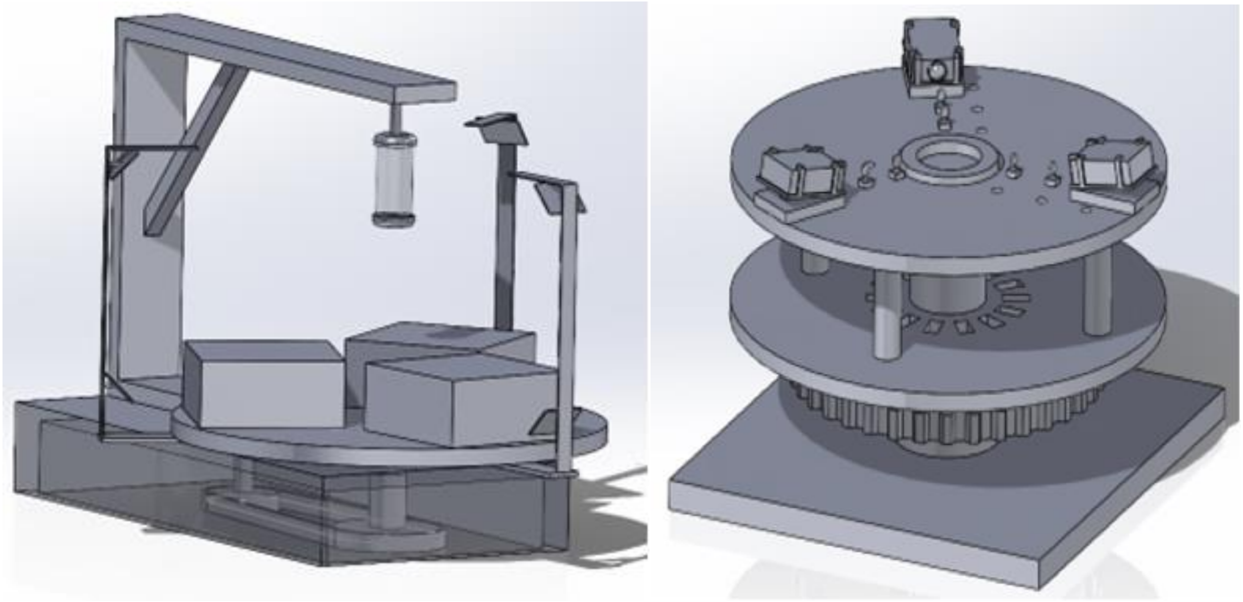


Figure 28: Designs using belt (left) and gear (right) driven systems

The concept that was ultimately manufactured was closely related to (Figure 28). After thorough consideration, dedicated testing, and the reasons previously mentioned, it was decided to use the EZCast Beam J2 projectors for the printer. This projector accomplishes all the requirements and specifications passing brightness, throw distance, power and physical requirements like weight and size. Along with this the resin that passed all characteristics and satisfied our availability needs was the clear ANYCUBIC 3D Printer Resin specifically for 405 nm UV. It was purchasable online for a low cost and could be cured using the 405 nm wavelength light. For the gear system, the disassembled parts of a polarizer that contained a 3:1 gear train were used. These parts were chosen because they were on-hand and fit the physical requirements necessary, which were strength and size. To make the system work, 3D printed spacers and fasteners were made to fit everything together. One of the EZCast projectors can be seen sitting on top of the circular rotating bed in (Figure 29), this rotating bed is essentially the large gear in the 3:1 gear train.

One of the concerns going into rotating the projectors was how to set up the controls and power to effectively rotate the projectors without damaging and twisting the wiring below. To get the wire management to be organized and to get power output to the projectors a slip ring was used so as not to twist, tangle, catch or damage any of the surrounding electronics. A slip ring, also known as a rotary electrical joint, is a device that allows for the transmission of electrical power and signals from a stationary structure to a rotating one. It is commonly used in electromechanical systems that require the transfer of power or signals between a stationary part and a rotating part. a slip ring is made up of a series of conductive rings and brushes that contact each other as the device rotates. The rings are stationary, while the brushes are mounted on the rotating part. As the device turns, the brushes slide over the rings, making electrical contact and allowing for the transfer of power or signals. A switch was also implemented so the system's power could be easily turned on and off as needed to prevent damage to motors while manually moving the rotating table or adjusting the height of the gantry while switching out resin or adjusting the code.

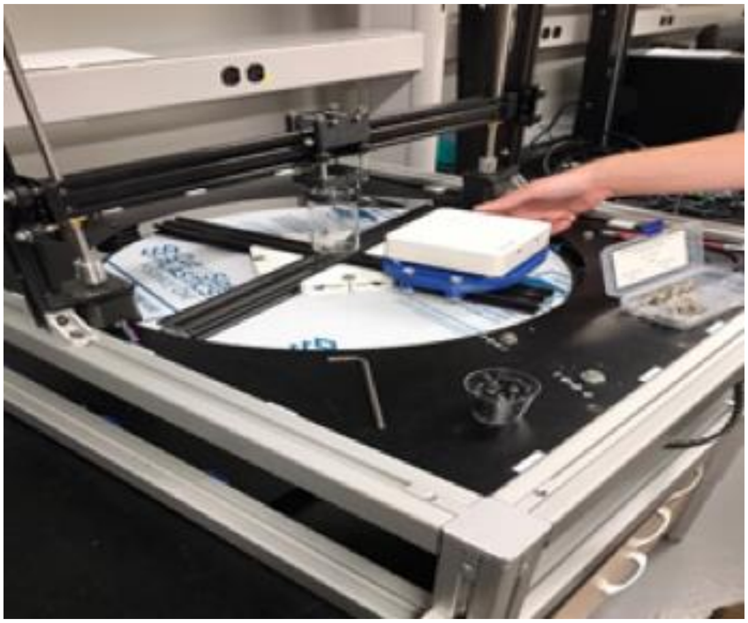


Figure 29: Initial concept gantry and projector setup

3.3.3 Second Step Design Build

Upon assembling the prototype, a few problems arose that were not taken into consideration in the initial concept evaluation. To achieve the smooth and stable rotation we were hoping for, we had to switch from the initial design concept of a direct 3:1 gear train to a supported gear-belt system. This is because the initial concept of the gear train didn't consider the amount of flexibility that came with the design and using the old parts of another machine. To resolve the stability problems presented by the gear train, the small gear was supported with a bracket and ball bearings. The final overall prototype and new concept rotary system can be seen in (Figure 30).

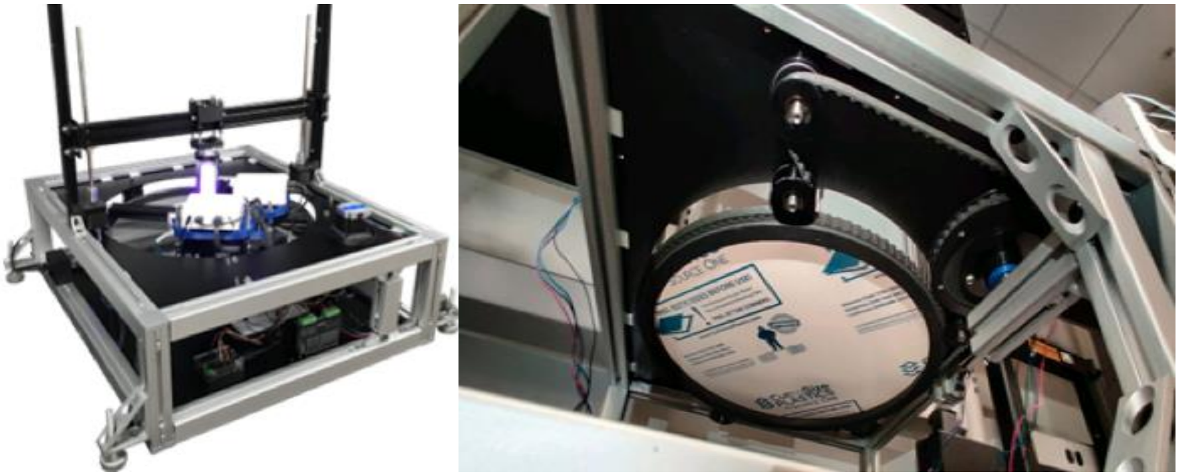


Figure 30: Final overall prototype (left) and new concept gear system (right)

The overall dimensions of the base were 28.9 x 24.52 x 8.97 inches. This does not include the 4 feet that protrude about 2 inches out on either side at the bottom of the base. The gantry stands 11.81 inches high from the top of the base and is as wide as the base of the printer. The gantry, with a holder for the resin vat is powered by two nema 17 motors, one on either side of the gantry. Each projector is 4.53 x 4.53 x 1.26 inches easily fitting on the rotating base. The rotating base itself is an acrylic circle 18 inches in diameter holding the rails and 3D printed adjustable mounts for the projectors. The base lays on the main gear (Figure 29) with an inner diameter matching the base plate. Connected by a gear tooth matching belt is another smaller gear whose is powered by the Nema23, seated in place by another 3D modeled coupler system. All mechanized parts are connected and controlled by an Arduino placed between the top and bottom levels of the base. The 3 motors connected to the power source and their respective controllers, each controller is connected to the power source and the Arduino.

The goal of this second step was to create a machine that works and proves conceptually that a Computed Axial Lithographic printer can be made with a rotating light source. The nature of this design allows for a tool-less removal of the rotating build plate, easily replaceable motor, and plenty of room to add components “under the hood”. There is plenty of room to add cameras, create new vial holders for larger tanks and add additional projectors. What has been proven with this machine is that adequate power can be provided from multiple smaller DLP projectors given that they use an LED or laser light source with no UV blocking filters built into the units. Multiple projectors may provide headaches with correct alignment but allow for much greater build times and sizes. It should be noted that since this machine uses commercially available and unmodified DLP projectors, the UV content should be reasonably safe with short term exposure. The machine can be easily and relatively painlessly upgraded to accommodate a larger vial and a more powerful motor.

3.4 Hybrid Design System

Once the second step concepts were implemented and tested to ensure printing results were not affected by the changes, the hybrid DIW system was designed. DIW was selected to be adapted with VAM printing due to its ability to be modified to deposit materials with accuracy and repeatability. Moving away from rotating the resin vat to rotating the projectors helped simplify the complexity of the DIW system design. All components of the DIW system were designed and 3d printed using a traditional FDM printer.

3.4.1 DIW Motion Control

The DIW system was operated using an Arduino Mega coupled with a R.A.M.P (RepRap Arduino Mega Pololu Shield) shield. The RAMP shield provides a modular platform controlling the hardware of a 3D printer. It features the ability to control multiple stepper motors, sensors and other components. The software running on the RAMP is Marlin 2.0. Marlin is an open-source firmware that is most used to control 3D printers. It gives the user the ability to control the hardware including motors, heaters and other sensors. This software is highly customizable, and the source code can be modified to suit our application with specific parameters. To operate the RAMP shield, Pronterface was used. Pronterface is an open-source graphical user interface (GUI) which is commonly used to control 3D printers. It provides the ability to send gcode commands to the printer and monitor the printing process. This software can control the movement of the stepper motors and any other sensors. The g code was created using Cura, which is an open-source slicing software. It is used to create g code from STL models created in CAD software.

3.4.2 DIW Movement Design and setup

The DIW system was incorporated on top of the second iteration to allow for minimal movement of the resin. If two different machines were constructed, the resin would have to be transported to the secondary machine causing potential shifts in the preprinted part. With limited space, the x-axis was setup with a belt system, the y-axis with a lead screw, and finally the z-axis with a rack and pinion design.

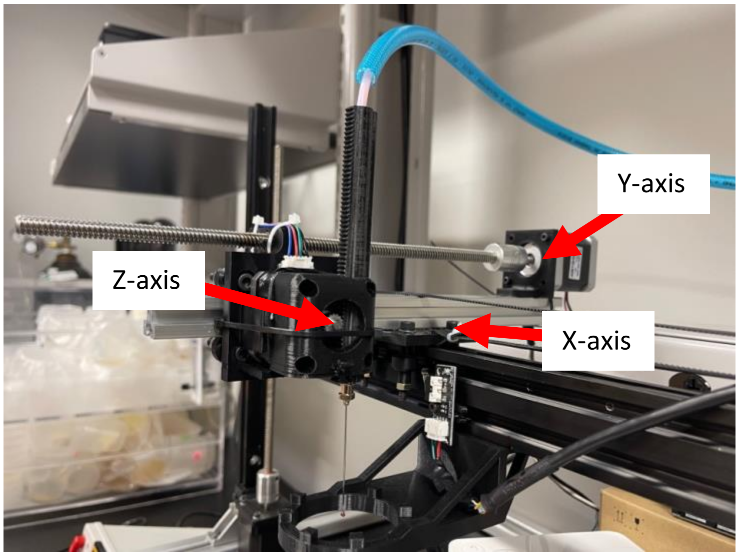


Figure 31: DIW System Configuration

The rate at which the secondary material flowed was 3.2 mm^3/second, while the step height was 0.8 mm. To avoid distorting the print, the speed of the DIW system was set to 10 mm/second since higher speeds caused the needle to agitate the resin. However, using lower speeds extended the overall process time. To deposit the secondary material into the resin vat, a 10cc syringe was utilized. This syringe was placed in a modified syringe pump that was linked to the R.A.M.P board and controlled through the same interface as the axis. Once the printing began, the syringe pump dispensed material at a constant rate through a tube to the 22-gauge needle. The needle started at the bottom of the resin vat and moved upward as the material was deposited. If any errors arose during operation, the printing process would be terminated, and fresh resin would be required.

Once the DIW process was nearly complete, at around 95%, the VAM system would start rotating. This was to allow enough time for the carousel to reach a speed of 35 degrees/second before the VAM process began. This ensured that the rotation speed was at the optimum speed for the VAM process. When the carousel reached the desired speed and the DIW process was complete, the projectors would switch from emitting a neutral color to the color representing the 405 nm wavelength. The purpose of this was to initiate the VAM process, which involved exposing the printed part to ultraviolet light to cure the resin and solidify the part. The VAM process typically took around 40 seconds of UV exposure to solidify the part. Once this process was complete, the projectors would switch back to the neutral color, and the projector lenses would be covered to prevent any UV bleed and solidify any uncovered resin. This also ensured that the finished part was not affected by any residual UV exposure. After the VAM process was complete, the carousel was stopped to allow for the resin vat to be removed from the holder. Forceps were then used to remove the part from the resin and was wash with 99% isopropyl alcohol for 20 to 30 seconds. This step was crucial as it removed any excess resin from the part and prepared it for the final curing process.

The next step was to cure any remaining resin attached to the part. This was done using a UV curing station, which exposed the part to a specific wavelength of ultraviolet light to finalize the curing process. The part was kept in the curing station for 1 minute and 30 seconds to ensure that all the resin was fully cured. It was essential to ensure that all parts underwent the same curing procedures to maintain consistency and avoid any variations. Overall, the entire process of creating a part using the DIW and VAM methods involved several critical steps, each of which played a vital role in achieving the desired result. By carefully following each step and ensuring that all procedures were consistent, the process could be optimized to produce parts efficiently and reliably.

CHAPTER FOUR: TESTING AND EVAUATION

4.1 Introduction

In this study, three different types of materials, flexible resin, hard resin, and the flexible shell with harden core, were tested to determine the impact of the different structure and printing method. It was noticed that with every run of the VAM, the resin was being exposed to UV light creating a change in the reflective properties of the material. During the testing of the VAM technique adjustment were made to keep the UV image within the boundaries of the resin. After repeated UV exposure with the same resin, the resin would reach a critical point where the resin could no longer achieve the same quality print, at which point it was replaced with fresh resin. The limit of the resin was dictated by the exposure time and the image size. As the image size increased, a larger area of resin was exposed to the UV light curing the resin slightly with every run. It was found that four to five runs could be achieved before replacing the resin with new unexposed resin.

4.2 Testing

4.2.1 Printing Resolution

All 3d printers have a margin of error from the CAD model to the actual part. DLP SLA and DIW printers have shrinkage properties depending on the type of material being used. By measuring the image or CAD model and comparing it to the printed part, a discrepancy can be found between the two. In this study, the VAM technique uses projection-based images that are passed through a liquid in which creates a refraction within the liquid. The light traveling through the liquid behaves differently and distorts the image. The image being displayed on to the resin was measured to be 17 mm in height by 12.6 mm in width. This image stayed consistent throughout the study and was checked between every print to ensure the image was not out of line or out of focus. If the image was out of focus, the blurry edges would create a bleed over and expose resin beyond the image’s boundary distorting the part.

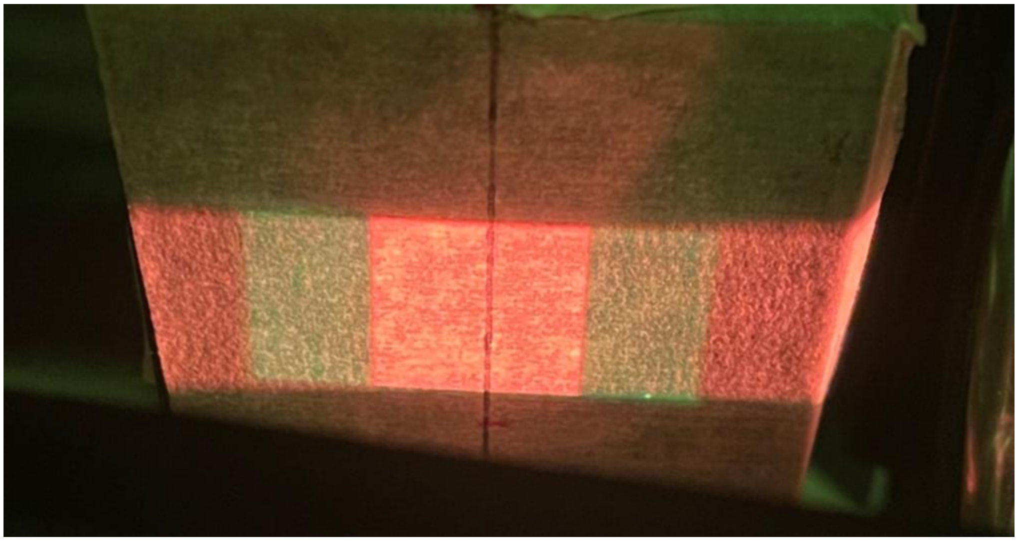


Figure 32: Neutral Image on Calibration Square

Figure 32 illustrates the calibration process using two projectors. One projector displays the image on the calibration square directly ahead, while the second projector, positioned 90 degrees from the first, displays the same image stretched across the calibration square. The stretched image is equally distributed on both sides to ensure the height of each projection is accurate and within the boundaries of the other image. This process is repeated with the second projector to confirm alignment. Once both projectors are calibrated, the resin is placed in the holding arm and exposed for different times (30, 35, 40, 45, 50, 55, 60 seconds). After each exposure, the resin is removed from the arm and the resulting part is cleaned with 99 percent isopropyl alcohol and cured for one minute thirty seconds in an ELEGOO Mercury curing station, which rotates the part under UV light to cure the remaining resin.

Figure 33: 30 Seconds Exposure Time, Flexible Resin

Figure 33 displays a sample that was exposed for 30 seconds, with a diameter of 8.26 mm and a height of 13.13 mm. The measured dimensions were 41.61% smaller in diameter and 25.69% smaller in height than the projected image. Additional samples were tested with longer exposure times resulting in larger parts. However, if the exposure time is too long, over-curing can occur, rendering the resin and the part unusable. During solidification, an opaque tint develops, starting from the center and propagating outwards. This "ghosting effect" is noticeable in Elegoo hard resin, but not in SuperFlex resin due to its refraction properties. This makes it difficult to detect over-curing in SuperFlex resin and stop it before it ruins the print.

Figure 34: 35 Seconds Exposure Time, Flexible Resin

Figure 35: 40 Seconds Exposure Time, Flexible Resin

Table 3: Percent Difference Between Sample and Image Size

	Samples Dimensions		Percent Difference	
A) 113 Super Flex	Diameter (mm)	Height (mm)	Diameter (%)	Height (%)
30s	8.26	13.13	41.61	25.69
40s	10.99	12.09	13.65	33.76
45s	15.32	13.83	19.48	20.56
50s	13.41	15.44	6.23	9.62
60s	11.73	14.45	7.15	16.22
B) SuperFlex				
30s	11.38	13.16	10.18	25.46
35s	13.55	16.4	7.27	3.59
40s	10.62	14.29	17.05	17.32
45s	10.21	14.5	20.96	15.87
50s	12.69	18.28	0.71	7.26
C) Elegoo				
30s	10.92	16.35	14.29	3.90
35s	10.89	16.38	14.56	3.71
40s	10.66	14.92	16.68	13.03
45s	11.55	16.85	8.70	0.89

The table presented above displays the percentage difference in height and diameter for each sample at varying exposure times. A combination of Ebecryl 113 and SuperFlex at a ratio of 1:4 was used in sample A. Ebecryl 113 is a low odour aliphatic monofunctional diluting acrylate. Sample A had a higher percentage difference in height at lower exposure times but decreased significantly at 50 seconds. The percentage difference in diameter for Sample A was less significant and decreased at 50 seconds. Sample B, which consisted of SuperFlex alone, had a smaller overall percentage difference compared to Sample A. However, when exposed for less than 35 seconds, it did not fully develop a part. Sample B was stopped at 50 seconds as overexposure caused the resin to become unstable and overcure. At 35 seconds of exposure, Sample B had the lowest percentage difference in diameter and height at 7.27% and 3.59%, respectively. Sample C, which used Elegoo resin, was noted to become overexposed and overcured after 45 seconds. At 45 seconds of exposure, Sample C had an 8.70% difference in diameter and a 0.89% difference in height. Other shapes were tested, and a cylinder was selected for its symmetry and larger inner area, making it easier for the DIW to deposit the secondary resin. Nozzle-like shapes with inner cavities were created using Elegoo resin.

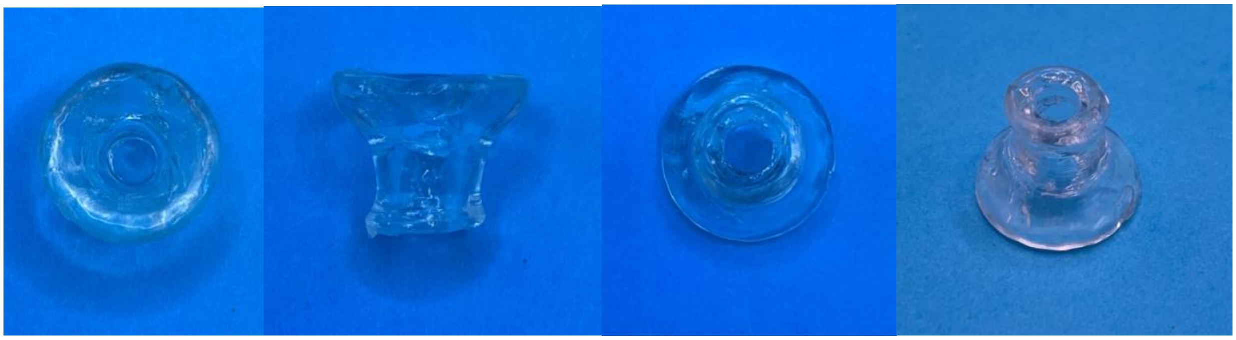


Figure 36: Nozzle Like Shape, 40 Seconds Exposer Time, Elegoo Resin

Figure 36 showcases the capability of creating parts with cavities, such as nozzles. The inner diameter of the nozzle was measured to be 2 mm, with an overall length of 5.94 mm. The larger diameter was 7 mm, while the smaller diameter was 4.6 mm. The inside of the nozzle displayed a well-formed circle, but the outer diameter appeared rough. This was caused by a misalignment in the projected image.

4.2.2: Hybrid DIW Printing

In the hybrid DIW-VAM system, the secondary resin was colored red to improve the visualization of the inner core. Proper alignment was critical to achieving high-quality prints. If the DIW needle was not centered correctly, the core would cure to the side of the cylinder, resulting in deformities, as shown in Figure 37.

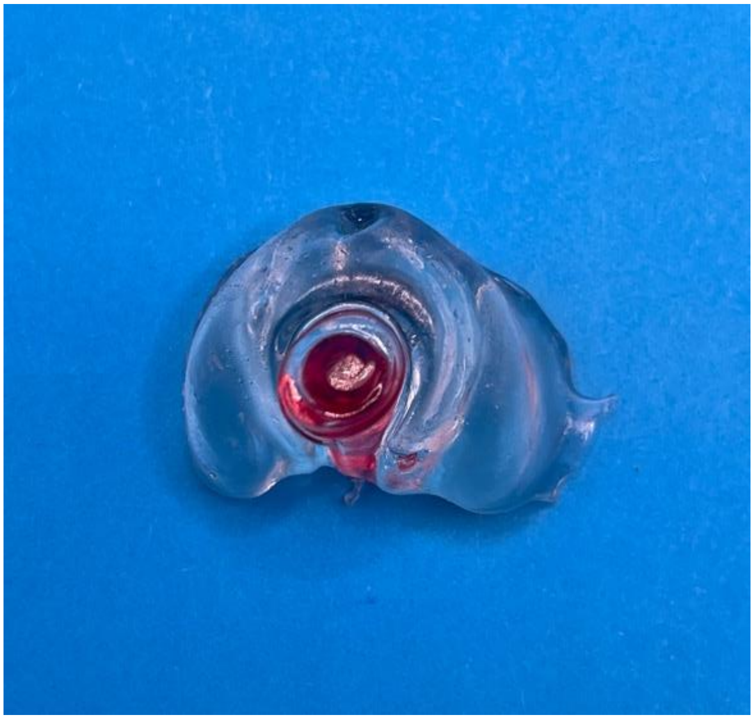


Figure 37: Miss Alignment of the DIW System

During DIW depositing, an issue arose due to the viscosity difference between the two resins, resulting in a ballooning effect. To address this issue, the slicing software parameters were modified and tested to minimize the effect, and it was discovered that a flow rate of 3.2 mm3/s was optimal. Increasing the flow rate led to more ballooning, as it built up pressure within the line, while lowering the flow rate did not deposit enough resin to be visible.

Another issue encountered was related to the secondary red Elegoo resin, which did not create enough surface tension to stick to the walls of the needle, causing continuous dripping. This dripping contaminated the top surface of the primary resin, creating a top layer of cured resin during the curing process. The secondary resin solidified faster due to its smaller surface area, causing the inner core to solidify first and descend out of the sight of projected images. To overcome this issue, the outer resin had to solidify at the same rate as the inner core, and to achieve this, the image was transformed into a gradient with a 30% transparency at the center, reducing the UV intensity.

Figure 38: First DIW VAM Hybrid Print

The output of a hybrid system print is presented in Figure 38, which has a diameter of 7.72 mm and a height of 17.34 mm. The red color within the print denotes the hardened core, while the surrounding material is flexible.

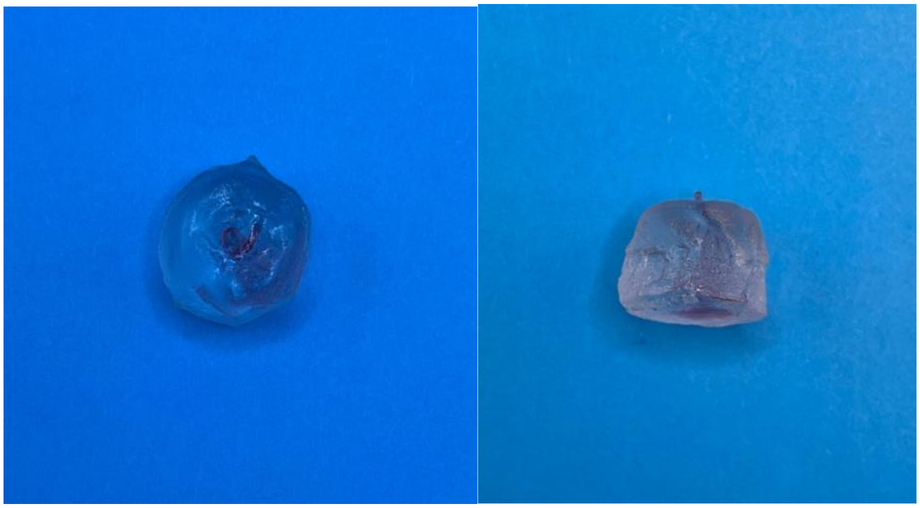


Figure 39: Second Hybrid Print

A hybrid print with a low flow rate is shown in Figure 39. Although the red core is less prominent, it was cured in the center of the cylinder. This print measured 11.40 mm in height and 13.58 mm in diameter and was cured in 40 seconds.

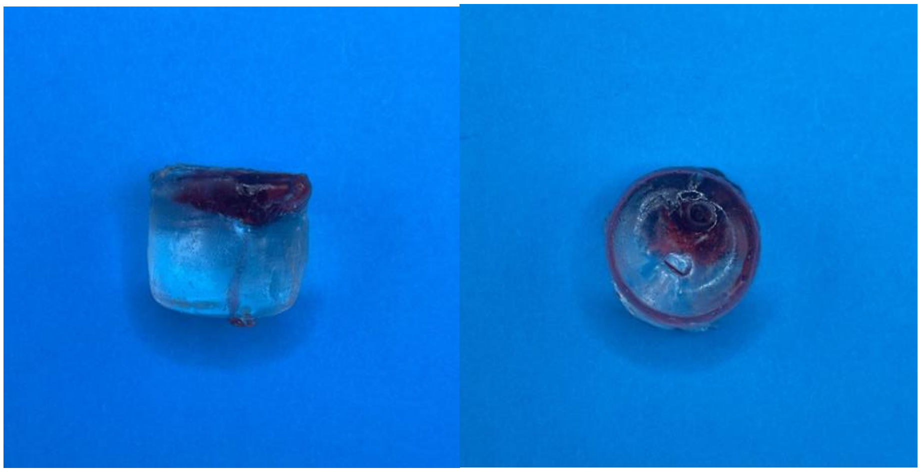


Figure 40: Third Hybrid Print

Figure 40 depicts a red resin pool visible at the top, which occurred due to the dripping of secondary resin during the VAM curing process. This resin dripping resulted in problems, as the resin would accumulate at the top, leading to an uneven mixture of red and clear resin, causing deformities if the remaining resin was reused without curing the secondary resin during the VAM process.

4.2.3: Compression Testing

All the parts were compression tested using a Test Resource 100 Series Universal Test Machines. The compression test is used to measure the maximum amount of compressive load a material can withstand before fracturing. The most common parts used for this testing are in shapes of cylinders. The testing was run at a rate of 5mm/min to ensure even testing throughout the parts. The load measuring accuracy meets or exceeds ASTM E4, ISO 7500/1, EN 10002-2, JIS B7721. ± 1.0% of reading down to 1/100th of load cell capacity. Its strain measurement accuracy meets or exceeds ASTM E83, BS 3846, ISO 9513, and EN 10002-4 standards. A compression tester works by measuring the force by a load cell and measuring the displacement using a cross head motion position encoder. These two data sets are then plotted with time to determine the behavior of the material and creating a stress strain curve. By Testing the materials in compression, the yield strength, compressive strength, ultimate strength, and the elastic modulus can be determined.

The following graphs exhibit the stress and strain curves of the compressed parts. These figures, numbered 41-50, compare the VAM-only method with the DLP printing method, while also displaying the Young's modulus of the parts. Each graph represents a different exposure time, starting from 30 seconds and increasing in 5-second intervals, up to 45 seconds.

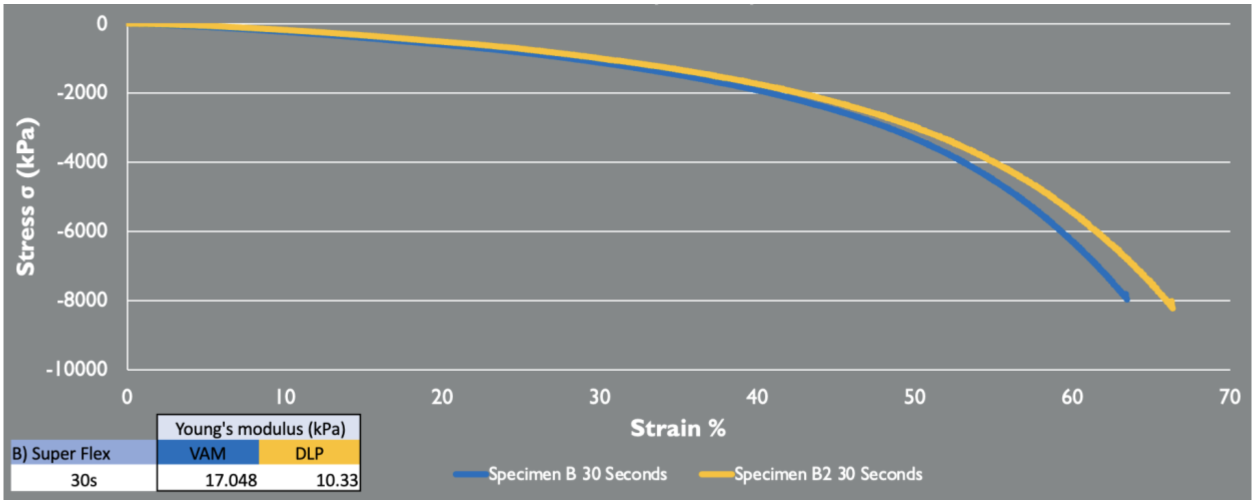


Figure 41: VAM vs DLP Sample B: SuperFlex

Figure 41 compares the performance of VAM and DLP at 30 seconds exposure using SuperFlex resin. This graph shows a correlation from 0% to 10%, followed by a tapering off. The yellow and blue colors denote the VAM and DLP specimens, respectively. This color code is consistent throughout figures 41-48 and 50. The Young's modulus of each graph is displayed at the bottom left. For the SuperFlex resin at 30 seconds exposure, the Young's modulus was found to be 17.048 kPa, while for DLP it was 10.33 kPa. A higher Young's modulus value indicates a material's ability to withstand more stress without permanent deformation.

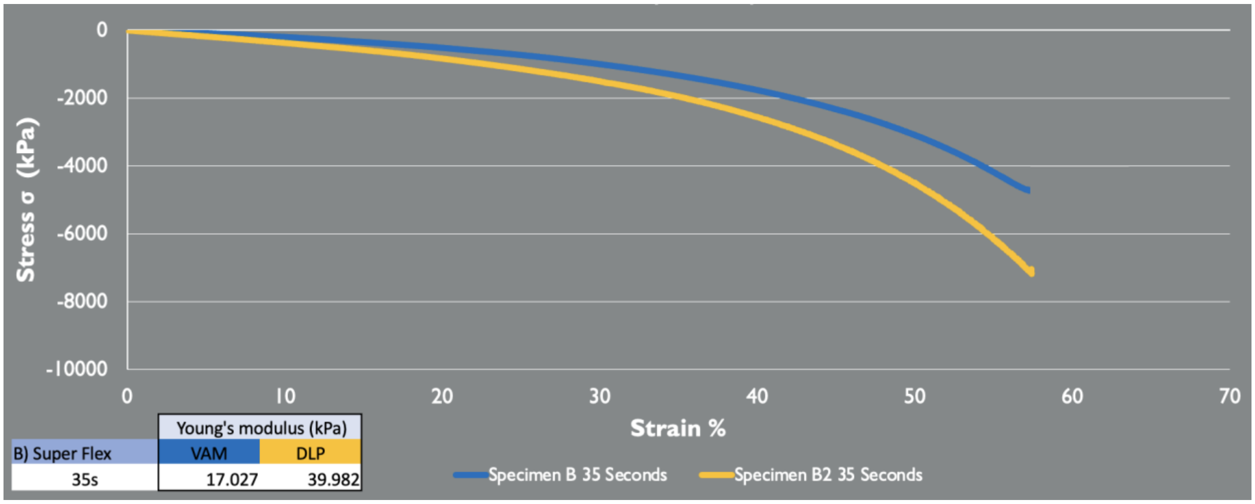


Figure 42: VAM vs DLP Sample B: SuperFlex

In figure 42, a greater deviation is noted from VAM to the DLP line. The young's modulus was found to be 17.02 kPa and 39.98 kPa, for VAM and DLP, respectively. This Young's modulus differs from figure 41. This can possibly be attributed to the unevenness of the surface of the DLP part as the VAM part maintained around the same Young's modulus.

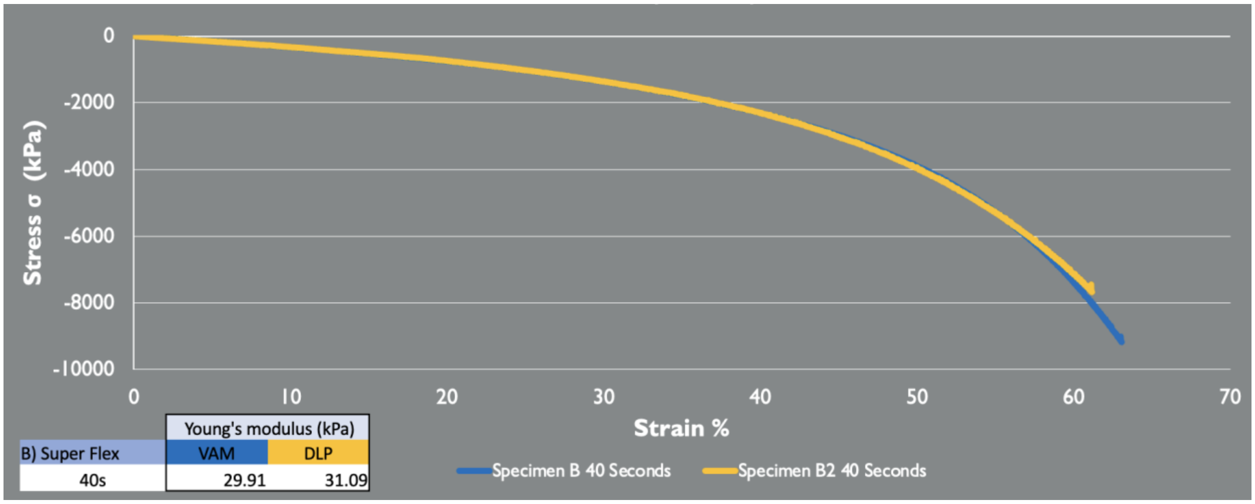
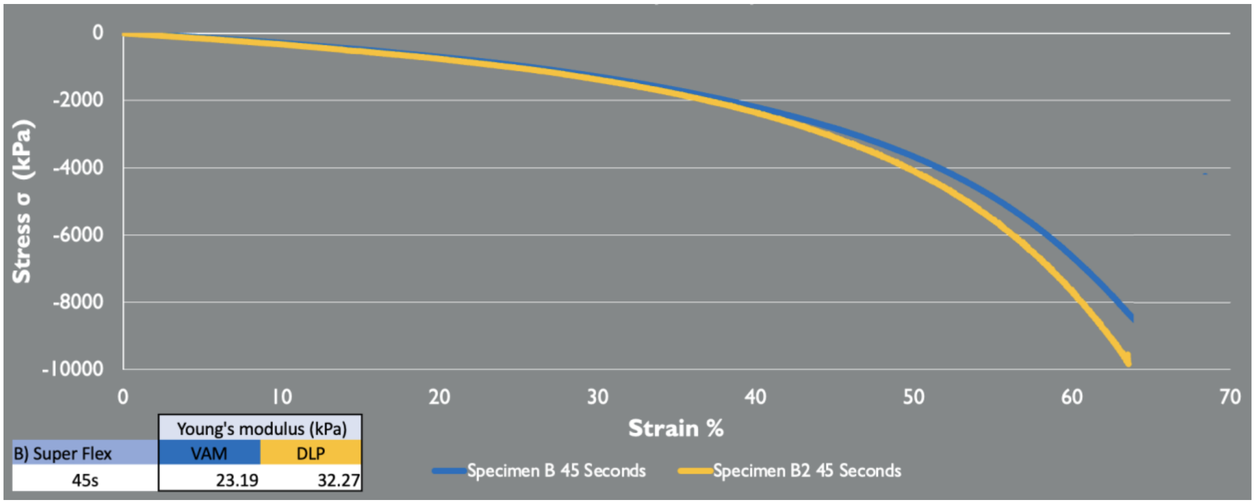


Figure 43: VAM vs DLP Sample B: SuperFlex

Figure 43 displays the samples at 40 seconds of UV exposure. VAM was recorded to have a Young's modulus of 29.91 kPa as compared to DPL's Young's modulus of 31.09 kPa. This graph shows a better correlation between the two methods and can be seen to result in the same stress and strain comparing two different printing methods.



	Young's modulus (kPa)	
B) Super Flex	VAM	DLP
45s	23.19	32.27

Figure 44: VAM vs DLP Sample B: SuperFlex

At 45 second exposure, figure 44 shows VAM at a Young's modulus of 23.19 kPa and DLP at 32.27 kPa. These two lines relate to each other up until 35% strain. Once passing 35% strain, the two lines split off and the DLP part can be seen to compress more under the stress as compared to the VAM method.

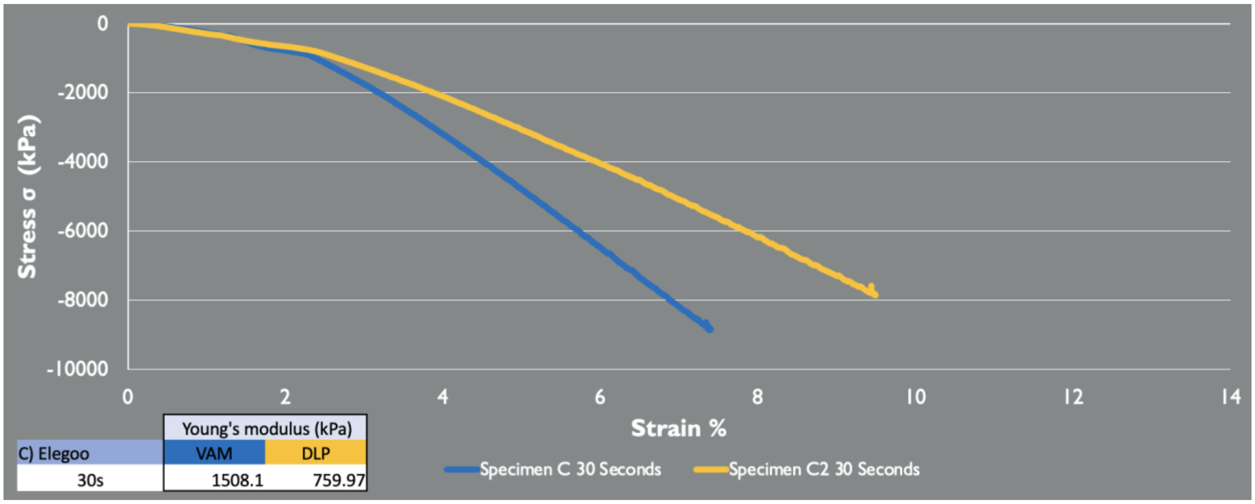


Figure 45: VAM vs DLP Sample C: Elegoo Hard Resin

Figure 45 displays Elegoo resin, which is the stiffer UV curable resin. From 0% to 2.3% strain, both VAM and DLP correlated. After 3% strain both lines deviate showing VAM to compress more with the stress. VAM Young's modulus was found to be 1508.1 kPa while DLP's Young's modulus was 759.97 kPa.

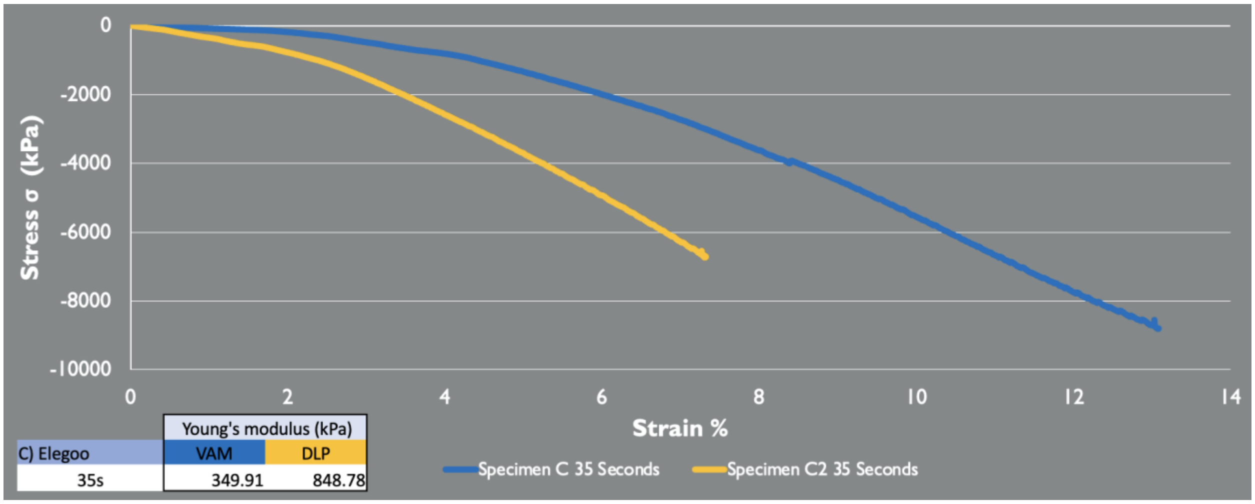


Figure 46: VAM vs DLP Sample C: Elegoo Hard Resin

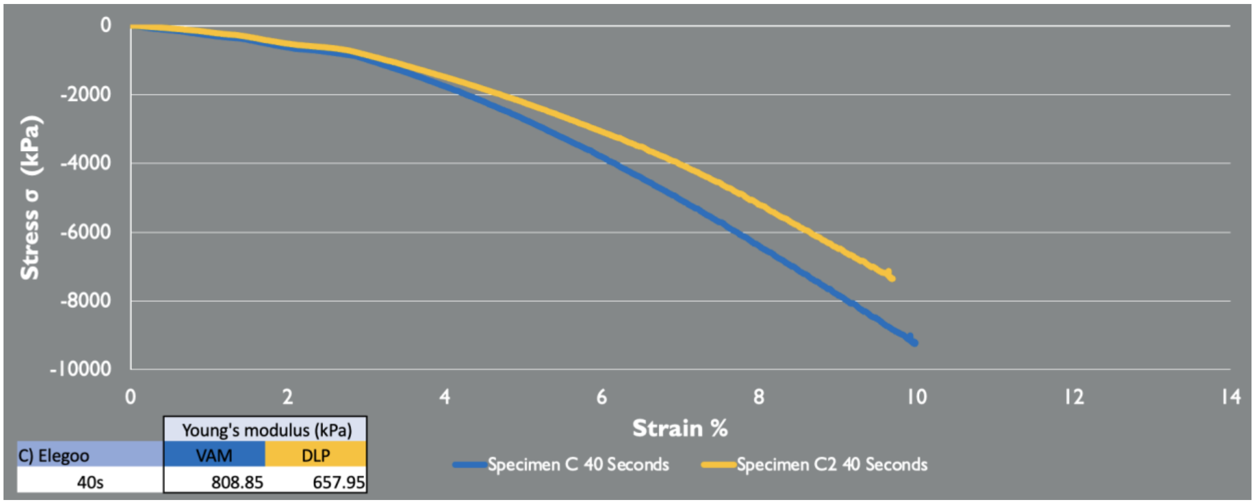


Figure 47: VAM vs DLP Sample C: Elegoo Hard Resin

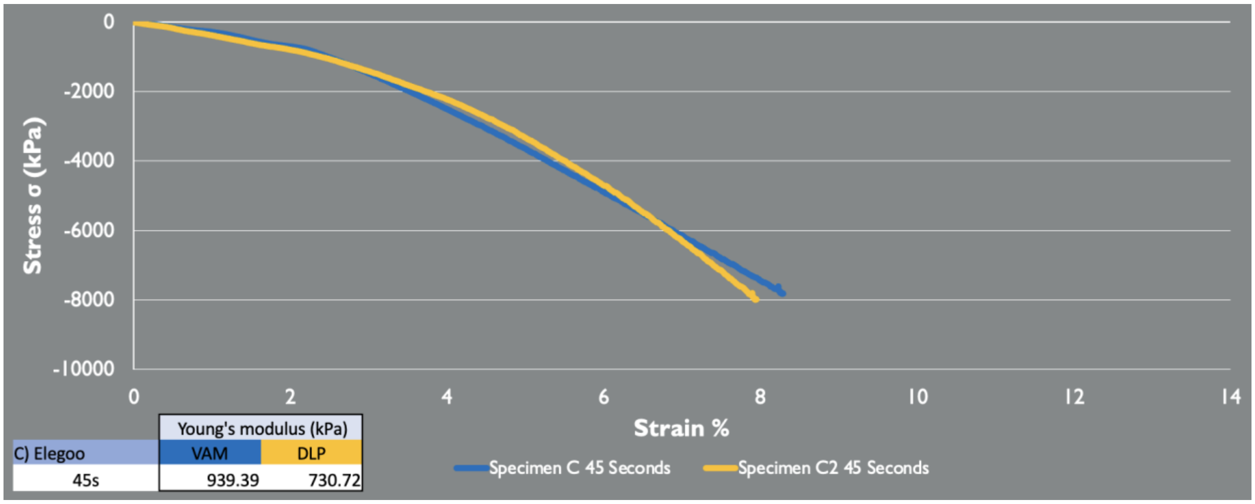
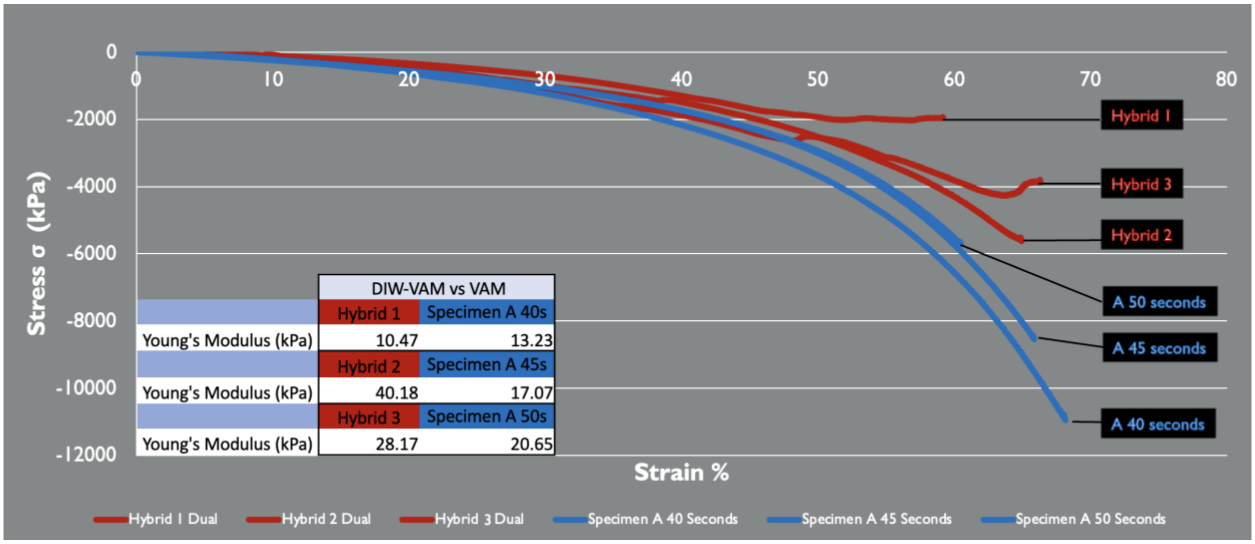


Figure 48: VAM vs DLP Sample C: Elegoo Hard Resin



	DIW-VAM vs VAM	
	Hybrid 1	Specimen A 40s
Young's Modulus (kPa)	10.47	13.23
	Hybrid 2	Specimen A 45s
Young's Modulus (kPa)	40.18	17.07
	Hybrid 3	Specimen A 50s
Young's Modulus (kPa)	28.17	20.65

Figure 49: DIW-VAM vs VAM

Figure 49 compares the hybrid prints with the VAM method and reports their respective Young's modulus. Specifically, the first hybrid print had a young's modulus of 10.47 kPa, while the VAM method yielded a higher value of 13.23 kPa. The Young's modulus of the VAM prints increased with the curing exposure time, whereas no such correlation was observed for the hybrid prints. One possible explanation for this disparity is that the introduction of a secondary resin in the hybrid prints could have caused deformities within the part, leading to either increased stiffness or weakened structure.

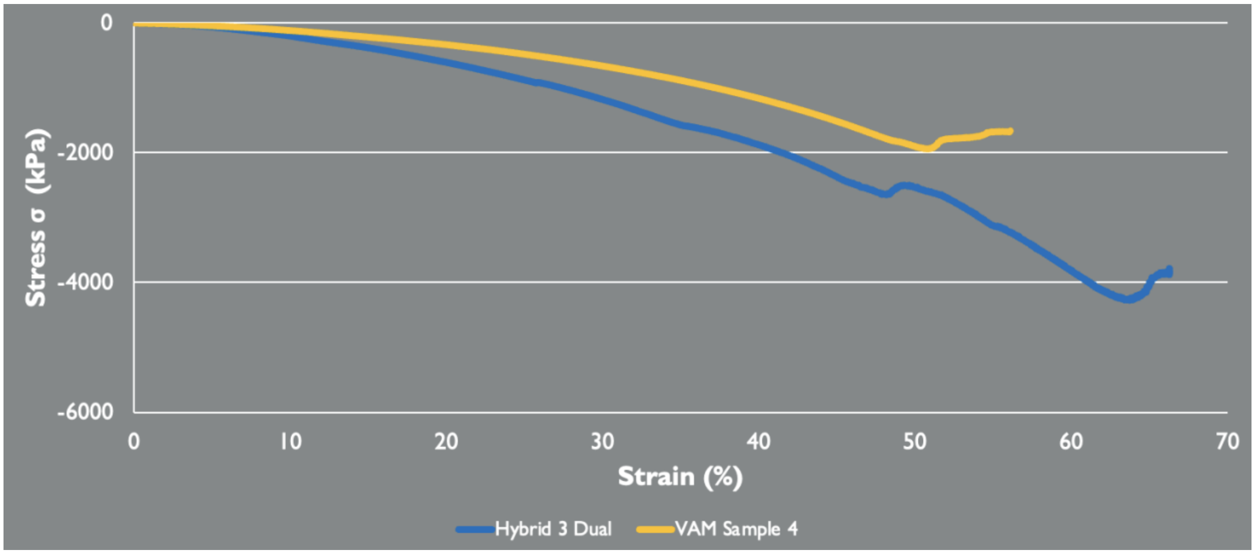


Figure 50: DIW-VAM vs VAM

In figure 50, it shows the testing of a hybrid sample that consist of a harden core with a soft outer shell. It is noted that at a strain of around 50% both samples give a trend upwards as the outer shell is compromised. The hybrid sample can be seen to withstand more compression due to its reenforced centered while the single material sample fractures early at 52% strain.

4.2.4: Temperature Testing

This section will explain the testing of the materials temperature behavior. A DataQ Four-channel USB thermocouple DAQ model DI-245 was used alongside a K-type thermocouple to record the temperature change of the resin through the curing process. The thermocouple was placed inside the resin in the section of were the UV light beams crossed. The temperature of the resin was measured to be at around 24 degrees Celsius. A simple cylinder was printed to collect the temperature data. UV resin can heat up during curing due to the exothermic reaction that takes place when the resin molecules react with the UV light. As the UV light penetrates the resin, it excites the photoinitiators present in the resin, causing them to release free radicals. These free radicals then initiate the polymerization process, whereby the resin molecules start to link together and form a solid polymer network.

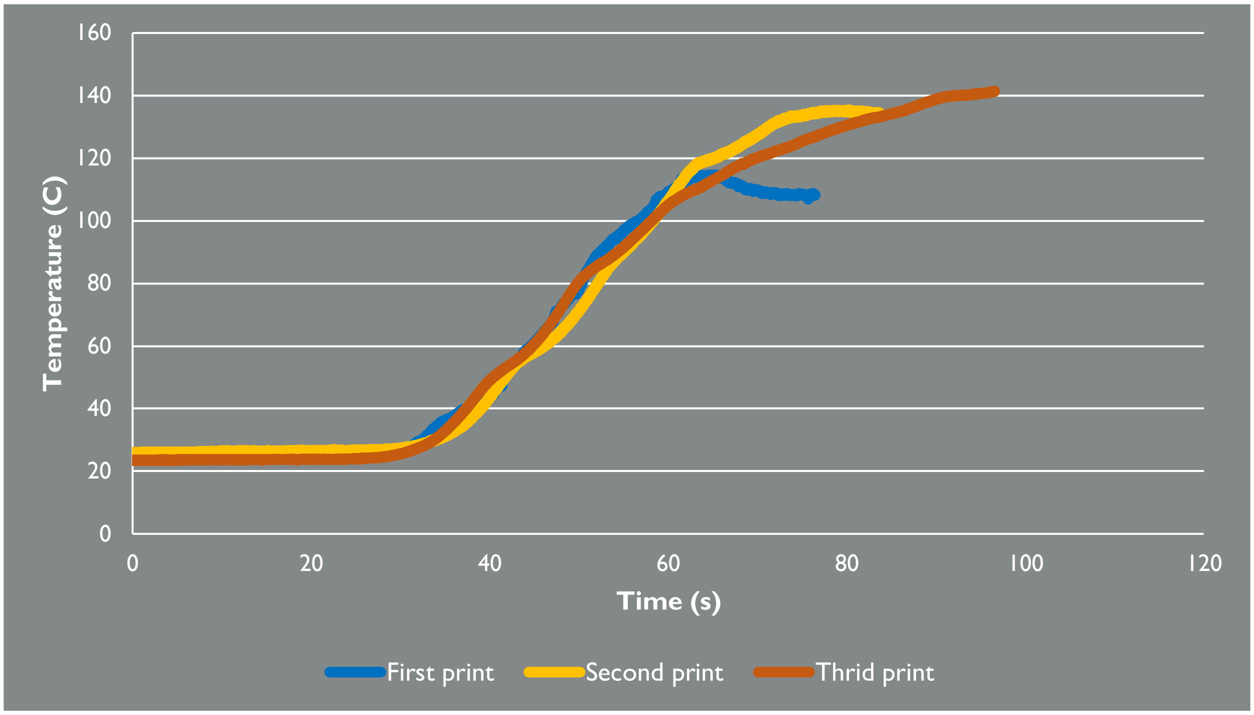


Figure 51: Elegoo Resin, Temperature Change Over Time

In figure 51, three prints were conducted using the Elegoo hard resin. At around 35 seconds the parts start to visibly cure. Around this mark the temperature starts to rise. For the first print, the test was stopped at 77 seconds and the temperature reached 108 °C. The second print was conducted for 84 seconds and a max temperature of 133 °C was recorded. Finally, the third print was prolonged to 96 seconds and reaching a temperature of 141 °C. The Elegoo resin was found to have a heat rate of around 3.2 °C/s. All prints after 60 seconds were deformed and not accurate. The prints were taken beyond 60 seconds to collect enough data to see the rate of change in temperature.

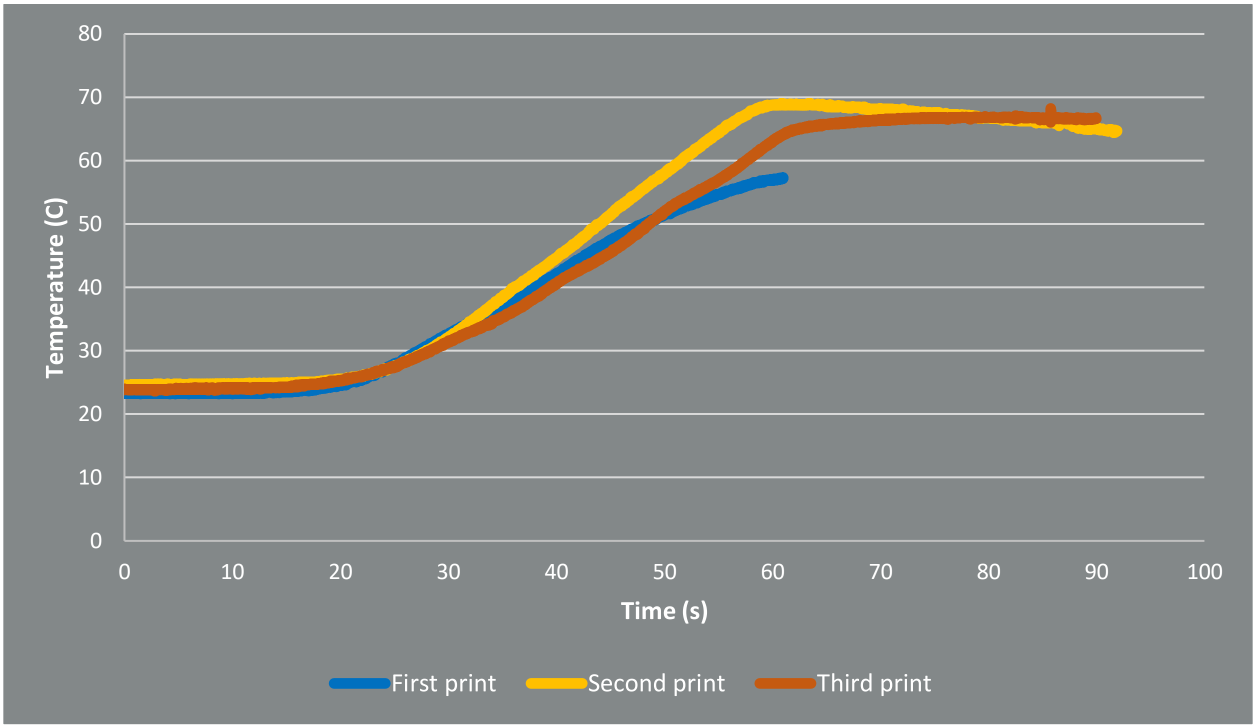


Figure 52: SuperFlex Resin Temperature Change Over Time

Figure 52 shows the change in temperature of the flexible resin, SuperFlex. The first print was terminated at 60 seconds with a max temperature of 60 °C. The second print was held for longer until 90 seconds and it reached a max temperature of 64 °C. Finally, the third print was also held for 90 seconds and had a max temperature of 68 °C. Both the second and third print tapered off at around 65 °C. The rate of temperature change for this material was found to be .97 °C/s. SuperFlex has a much lower rate of change compared to the Elegoo hard resin.

CHAPTER FIVE: CONCLUSION AND FUTURE WORK

This thesis demonstrated the hybrid method of combining DIW with VAM. VAM is a developing method that has room for expansion in the way this study has demonstrated. With the limited resources provided during this study, VAM has proven to be a method that can be developed for commercial use with off the shelf components. DIW has demonstrated its ability to be heavily modified to work around the VAM system. The quality of the prints largely depends on the accuracy and power of the projectors. With the projectors providing .471 watts of power per centimeter, being able to produce these prints in less than one minute is a great accomplishment. To ensure prints of high quality, the projectors are needed to be calibrated and ensured the image is in focus. Both projectors need to be aligned properly with the image adjusted to be at the correct level for hardening resin to keep from floating. The DIW system needs to be calibrated and primed to ensure the line is clear of any air pockets. The needle of the DIW system needs to be placed in the center of the projected image to ensure the dispersion of the secondary resin is in line with the UV light. If the needle is off center, the parts will cure unevenly and create a half-cured cylinder. A significant accomplishment achieved was that the prints were becoming more precise and consistent. Results became more predictable based on the number of times the resin had been used and the shape that was projected.

5.1 Future Work

Throughout the duration of this research, multiple parameters were identified as candidates for updates or changes. To optimize the performance of the projectors, it is recommended that an updated version be acquired for future iterations that emits only the necessary 405 nm wavelength with increased power. This will reduce power loss and enhance the resolution and quality of printed parts by eliminating the display of unnecessary colors. To minimize distortion during curing, a feedback loop to adjust the UV intensity of projectors in real-time would be helpful. An improved image processing method could also be developed to create asymmetrical shapes and improve print quality. To achieve high-quality prints, it is essential to rotate the image at the same speed as the projectors when creating asymmetrical parts. Implementing these improvements will decrease curing time and improve the accuracy and quality of prints.

To further improve the system, the next step is to eliminate the rotational components and design a two-wavelength curing method. Instead of rotating projectors, mirrors can be rotated around the resin vat to minimize vibrational errors and enhance projector adjustments. A custom bracket that allows mirrors to rotate around the resin vat while keeping the image static will be necessary. This will enable the projector to be modified and adjusted more accurately without interference from the system's rotation.

Developing an in-house resin capable of curing under two wavelengths would also be advantageous. One possibility is to create a resin that can cure under 385 nm, followed by 405 nm, which would produce different mechanical characteristics. This approach requires the introduction of a secondary projector that emits a different wavelength. Additionally, the resin will need to address the issue of floating, as the density of the part changes during curing. To mitigate buoyancy issues, maintaining the same or similar density throughout the curing process is critical.

In addition to the improvements mentioned above, further research can be done on the materials used for 3D printing. Developing new resins with higher viscosity and reaction temperature could help address the issue of floating and sinking during the curing process, which can result in inaccuracies in the size and quality of printed parts. Researching different types of resins and their properties could also lead to the creation of more durable and functional parts.

Furthermore, the development of a two-wavelength curing method could have many applications in various industries. For example, in the medical field, it could be used to create medical devices that require different mechanical properties in different areas. In the aerospace industry, it could be used to produce lightweight and strong components for spacecraft. There is a vast potential for this technology to be applied in many different fields.

Another potential avenue for further research is the integration of artificial intelligence (AI) into the 3D printing process. By using AI to optimize the printing parameters and adjust them in real-time, it may be possible to further improve the accuracy and quality of printed parts. Additionally, AI could be used to identify defects in printed parts and suggest adjustments to the printing process to address them.

In conclusion by making improvements to the system and materials used, and by exploring new applications and integrating AI, this technology can be further developed and expanded to benefit many industries.

APPENDIX A: G CODE COMMANDS

G0 - go to G1 code

G1 - Coordinated Movement in the X and Y

G2 - Clockwise Arc

G3 - Counter Clockwise Arc

G4 – Dwell time in S<seconds> or P<milliseconds> G28 - Home all Axis

G90 - Use Absolute Coordinates

G91 - Use Relative Coordinates

G92 - Set current position to coordinates given

APPENDX B: FIRST ITERATION MANUAL

when you start up the pi you have to nagivate to the folder containing the files for projecting.

first, you gotta open the terminal. press ctrl+alt+t

then to navigate to the folder that has the python scripts type

```
cd Desktop\photoreplicator\Projections
```

now to start the program you type

```
python3 generateShape.py SHAPE
```

the shape is determined by whatever shape you type to replace SHAPE
The available shapes are pretty confusing, but they are as follows:

rectangle - draws a rectangle
circle - draws a circle
pawn - draws a pawn
polygonRect - draws a rectangle -- this is the one I use whenever I draw a rectangle to the screen
cup - draws a thin walled cup
cupClass - draws a thick walled cup
cone - draws a triangle to print a cone

so if you wanted to print a sphere type

```
python3 generateShapeMotorTest.py circle
```

once the program opens the controls are as follows:

MOTOR CONTROL
Q - turns on the motor to rotate the central motor
W - turns off the motor to rotate the central motor
E - (DONT USE) turns on the motors to rotate the lead screw motors
R - turns off the motors to rotate the lead screw motors

SHAPE CONTROL
Z - increases the size of the object
X - decreases the size of the object
LEFT ARROW - moves the object to the left
RIGHT ARROW - moves the object to the right
UP ARROW - moves the object up
DOWN ARROW - moves the object down

STARTING EXPERIMENTS
ENTER - starts the resin hardening

APPENDX C: SECOND ITERATION CODE

//To simply run the code, all the users must do is simply press the check icon or verify key and then the right arrow icon or upload key at the top left of the program code to compile and run the code. Next the user should open the serial monitor by clicking on the magnifying glass icon at the top right. This series of prompts will then appear after a certain number of seconds:

> "This program is to be used for the V3DP teams that want to control the motors"
> "To start, enter the word Start into the Serial box above and send it to the Arduino."
> "To control the motors, here are the options: up, down, rotate, stop, exit, numbers, timer"
> "These controls can be utilized at any time but not twice. Each control does exactly its name."
> "The program will begin in a few seconds."

Once the user has read these options, they then should type in the word "start" in the serial box and press enter or click send. This will then start the program allowing for control of the motors which is rotation of the platform and gantry movement. The function of each keyword is as follows: if the word "up" is sent to the Arduino, it will cause the lead screw motors to spin up a certain distance i.e., move tank out of print area. If the word "down" is sent to the Arduino, it will cause the lead screw motors to spin down a certain distance i.e., move tank into print area. If the word "rotate" is sent to the Arduino, it will cause the continuous motor to start spinning. If the word "stop" is sent to the Arduino, it will cause the continuous motor to stop spinning. If the word "exit" is sent to the Arduino, it will cause the program to stop entirely. If the word "numbers" is sent to the Arduino, it will display all information from the program. If the word "timer" is sent to the Arduino, it will initiate a timer-based control for central motor. Any of these options can be called at any point while the program is running, if the motor control has started through the "start" action, and it's not called twice.

```
// These defines are specific to the setup and needs (should be checked and changed if setup changes)
#define DegPerSec          180        // degrees per second (speed, higher value scales to lower delay intervals)
#define ChangeInInches      4.8        // height to move gantries up and down (in inches)

// none of the variables below need to be changed as they are set in the rest of program
// unsigned long variables are used to record the current code milliseconds when an action is called (timekeeping)
unsigned long rotateRunMillis;            // holds the current ms of performing an action (rotate or stop) on the continuous motor, corrects calculations in the "timeChange" method
unsigned long holdTimeMillis;          // corrects the calculation in the "timeChange" method, its essentially adds to the last amount of a 5000 ms interval
unsigned long currentMillis;         // records the current time in milliseconds
unsigned long startMillis;          // starts the milliseconds timer, called in the "start" action of the code
unsigned long timerMillis;             // called when "timer" action is called, corrects time based calculations
unsigned long codeMillis;          // same representative value that helps determine how long the code runs until a certain point (used in tangent with currentMillis and performs same function)
```

```
unsigned long elapsed;          // represents the time between startMillis and the point currentMillis
is called
unsigned long Secs;        // amount of seconds the "timer" action should run, is in ms so any value
should have three zeros added to the end of it

// regular initiated variables
int motorArray[7];         // array used to hold the motor pin values and steps per rev for motors
int stepCountCont;         // counter used to represent the number of counts the continous motor has
progressed to
int codeRunTime;           // corrects the speed (step delay) calculation based on the perceived # of
ms the code takes to actually step the motor
int tempChange;          // temporary holder value for "rotate" and "stop" actions to push the start
speed in speed array a value forward
int increment;         // traverses the speed array in the "runContMotor" method
int moveDown;         // represents the current systems gantry positions, this will be 0 if system is
up otherwise its -1
int moveUp;        // represents the current systems gantry positions, this will be 1 if the system is
up otherwise its 0

float delayForGantry;        // speed (step delay) for the gantry motors to spin
float contMotorRevs;        // used to convert the number of steps the continuous motor has rotated
(stepCountCont) into number of revolutions
float timerMins;         // used to convert the number of seconds the timer is supposed to run (Secs)
into minutes
float stepDelay;         // speed (step delay) for the continuous motor to spin
float constant;           // represents the constant used to correct the speed calculation (currently
controls the speed more than DegPerSec)

String tempHold;        // temporarily holds the value given from userOption in string comparisons
in the "loop" method
String userOption;         // the phrase or action sent to the arduino by the user

boolean steadyState;          // represents if the continuous motor will start rotating or not
boolean continuous;        // represents if the continuous motor will run continuously or not
boolean timeCheck;          // represents if the "timer" action has been called, will start time-based
action
boolean timeDone;       // represents if the program time has surpassed time limit, will end progrma
if it has
boolean userHold;        // represents if the last action given was already called, prevents an action
from being called twice
boolean motorRot;        // represents if the program wants to run motor control
boolean acceled;       // represents if the continuous motor has acceled or not, if has then the motor
will run continously
boolean accel;           // represents if the continouous motor needs to accelerate, if it does then
functions for incrementally speeding up will start
```

```
// method to set up arduino pins and serial monitor
void setup() {
  // lines define which pins go into array positions to be utilized in methods/loops
  motorArray[0] = 4;          // PUL of motor 1 should be this arduino pin #
  motorArray[1] = 5;          // DIR of motor 1 should be this arduino pin #
  motorArray[2] = 8;          // PUL of motor 2 should be this arduino pin #
  motorArray[3] = 9;          // DIR of motor 2 should be this arduino pin #
  motorArray[4] = 12;         // PUL of motor 3 should be this arduino pin #
  motorArray[5] = 13;         // DIR of motor 3 should be this arduino pin #
  motorArray[6] = 800;        // # of motor steps for a full revolution

  // Sets all the pins to be able to communicate
  pinMode(motorArray[1], OUTPUT);
  pinMode(motorArray[3], OUTPUT);
  pinMode(motorArray[5], OUTPUT);
  pinMode(motorArray[0], OUTPUT);
  pinMode(motorArray[2], OUTPUT);
  pinMode(motorArray[4], OUTPUT);

  // Values to be initialized and changed depending on need
  acceled = false;
  userHold = false;
  timeDone = false;
  motorRot = false;
  timeCheck = false;
  continuous = false;
  steadyState = false;

  moveUp = 1;         // 1 means the system is in the up position
  moveDown = 0;         // 0 means the system is in the down position
  Secs = 30000;         // variable for timer length (add 3 zeroes to end of value because value is in
milliseconds)
  increment = 0;          // self-explanitory, the increment number at start of program
  codeRunTime = 37;           // about how long it takes for program to traverse code
  stepCountCont = 0;           // since motor isnt assumed to be running at start of program, is set to
0
  holdTimeMillis = 0;           // a time interval of 5000 ms has not been done so this is set to 0
  delayForGantry = 2.0;          // sets gantry movement speed (ms)

  // unused calculations
  //constant = (DegPerSec * ( DesiredStepDelay + (codeRunTime * (180 / DegPerSec)) )) / 100;
// this equation calculates the constant that should be for a delay corresponding to a specific deg
per sec
  //stepDelay = ((constant * 100) / DegPerSec) - (codeRunTime * (180 / DegPerSec));           //
currently set so the delay is 5 ms (constant of 45 solves to final delay of 5 which is 180 deg per
sec physically)
```

```
  stepDelay = (7020.0 / DegPerSec) - (codeRunTime * (180 / DegPerSec));        // this is the speed
that the user wants the continuous motor to run at (calculates to a step delay of about 2.1 seconds
currently)

  // Sets up serial monitor and gives delay between setup and starting code
  Serial.begin(9600);
  delay(3000);

  // Print statements for user to understand how to use program
  Serial.println("This program is to be used for the V3DP teams that want to control the motors");
  Serial.println("To start, enter the word Start into the Serial box above and send it to the
Arduino.");
  Serial.println("To control the motors, here are the options: up, down, rotate, stop, exit, numbers,
timer");
  Serial.println("These controls can be utilized at any time but not twice. Each control does exactly
its name.");
  Serial.println("The program will begin in a few seconds.");
  Serial.println("");
  delay(3000);
}

// this method will step the single motor that runs continuously (only runs one direction)
void stepContMotor()
{
  // this line sets the motors current direction of motor 3 (options are HIGH or LOW)
  digitalWrite(motorArray[5], HIGH);

  // sends low / high voltages to the PUL pin of motor 3 (i.e. steps motor)
  digitalWrite(motorArray[4], HIGH);
  digitalWrite(motorArray[4], LOW);
}

// this method will control speed of the single motor that runs
void runContMotor()
{
  // Some variable initializations
  //codeMillis = millis();
  int divider = DegPerSec / 45;          // divides the deg per sec into intervals of 45 (4 intervals if
degpersec is 180)

  float speedArray[divider];            // initiates an array that will hold the speed values the motor
should run at
  float accelDelay;          // temporary holder for step delay that is used for accelerating

  // fills array with values for speed
```

```
  for (int i = 0; i < divider; i++)
    speedArray[i] = 45.0 * (i + 1);

  // checks current state
  // if program first started then motor should accel up to speed, if motor already running near speed
then motor should run
  //   continuously, lastly if the user wants to stop the motor safely then motor should decelerate
  if ((accel == true) && (acceled == false) && (continuous == false))
  {
    // this function accelerates motor to desired speed in 5 second increments (20 seconds overall to
reach speed)

    // checks if it has been 5 seconds
    currentMillis = millis();
    timeChange(currentMillis, rotateRunMillis);

    // checks if the timeChange method recognized an interval and then increases spped
    //   if no change then just continues with current delay (initially should equal 1 to start sequence)
    if (tempChange == 1)
    {
      accelDelay = (7020.0 / (speedArray[increment])) - (codeRunTime * (180 /
(speedArray[increment])));          // calculates step delay depending on current speed to run
      increment++;          // changes so next value in the speed array will be used for the accel delay
calculation
    }

    // checks current delay has reached desired delay (fastest speed), if it has then reset and change
constants
    if (accelDelay <= stepDelay)
    {
      Serial.println("Speed reached..");
      increment = 0;          // resets increment value
      acceled = true;          // represents that the motor has finished accelerating
      continuous = true;          // represents that the motor should run continuously
      accelDelay = stepDelay;          // reset accelDelay so the motor runs at the desired step delay
    }

    // resets tempChange variable
    tempChange = 0;
  }
  else if ((accel == false) && (acceled == true) && (continuous == true))
  {
    // this function will decelerate motor in 5 seconds increments (25 seconds overall to reach 0)

    // checks if it has been 5 seconds
    currentMillis = millis();
```

```
    timeChange(currentMillis, rotateRunMillis);

    // checks if the timeChange method recognized an interval and then decreases spped
    //   if no change then just continues with current delay
    if (tempChange == 1)
    {
      accelDelay = (7020.0 / (speedArray[divider - (increment + 1)])) - (codeRunTime * (180 /
(speedArray[divider - (increment + 1)])));        // calculates step delay depending on current speed
to run
      increment++;         // changes so next value in the speed array will be used for the accel delay
calculation
    }

    // checks current delay has reached desired delay (slowest speed), if it has then reset and change
constants
    if ( accelDelay >= ((7020.0 / (speedArray[0])) - (codeRunTime * (180 / (speedArray[0])))) )
    {
      Serial.println("Speed reached...");
      increment = 0;         // resets the increments
      acceled = false;           // represents that the motor is not acceled and would make sure it is if
spun up again
      continuous = false;          // represents that the motor shouldnt run continuously, should accel
first
      steadyState = false;          // ends continous motor function since the motor doesnt want to be
run anymore
      accelDelay = 1000;         // random value, makes motor spin really slow if error in steadyState
    }

    // resets tempChange variable
    tempChange = 0;
  }
  else if ((accel == true) && (acceled == true) && (continuous == true))
  {
    // running this takes 17 ms of code runtime
    accelDelay = ((7020.0) / DegPerSec) - (codeRunTime * (180 / DegPerSec));         // this should
be the same as stepDelay
  }


  // These lines are used to determine the code runtime (correct speed calc. errors, make sure to
uncomment the codeMillis line if using)
  /*
  currentMillis = millis();
  Serial.println(codeMillis);
  Serial.println(currentMillis);
```

```
  Serial.print("Current delay: ");
  Serial.println(accelDelay);
  */
  stepContMotor();
  delay(accelDelay);
}

// this method will step the two motors connected to PUL and PUL2 pins
void stepGantryMotors()
{
  // sends low / high voltages to the PUL pin of motor 1 (i.e. steps motor)
  digitalWrite(motorArray[0], LOW);
  digitalWrite(motorArray[0], HIGH);

  // sends low / high voltages to the PUL pin of motor 2 (i.e. steps motor)
  digitalWrite(motorArray[2], LOW);
  digitalWrite(motorArray[2], HIGH);
}

// this method will move the gantry a certain distance depending on which direction
void moveGantryMotors(int direc)
{
  // calculates the distance needed to move the gantries (changes anything in the current setup
changes)
  int stepsForDistance = ChangeInInches / ( (0.3125) / motorArray[6] );

  // move gantry up
  if (direc > 0)
  {
    for (int i = 0; i < stepsForDistance; i++)
    {
      // for each step, guarantee the motors spin the same direction
      digitalWrite(motorArray[1], LOW);
      digitalWrite(motorArray[3], LOW);

      // calls the method to step the 3rd motor
      stepGantryMotors();

      // stops motor voltage change (speed between each step)
      delay(delayForGantry);
    }
  }

  // move gantry down
  if (direc < 0)
  {
```

```
    for (int i = 0; i < stepsForDistance; i++)
    {
      // for each step, guarantee the motors spin the same direction
      digitalWrite(motorArray[1], HIGH);
      digitalWrite(motorArray[3], HIGH);

      // calls the method to step the 3rd motor
      stepGantryMotors();

      // stops motor voltage change (speed between each step)
      delay(delayForGantry);
    }
  }

  Serial.println("Gantry movement done.");
}

// this method just checks time, and if desired will end motor rotation
void elapsedTimeCheck(unsigned long currMillis, unsigned long starMillis)
{
  // compares current to startMillis
  if ((currMillis - starMillis) >= Secs)
    timeDone = true;
}

// this method is used for acceleraing/decelerating motor
void timeChange(unsigned long currMillis, unsigned long runStartMillis)
{
  // time variable for comparison and corrector
  unsigned long tempMillis = 5000;
  unsigned long correctorMillis = runStartMillis + holdTimeMillis;

  // if there is a 5000 ms difference between currentMillis and last check time
  //   then indicate a change and replace hold
  if ((currMillis - correctorMillis) >= tempMillis)
  {
    tempChange++;         // represents that the speed should change
    holdTimeMillis = (currMillis - correctorMillis) + holdTimeMillis;           // changes holdtime
millis to calculation from currMillis is actually a new 5000 interval
  }
}
// loop runs continuously no matter what unless signified to end
void loop()
{
  // motor running wont start until the program is initiated to start
  if (Serial.available() > 0)
```

```
    userOption = Serial.readStringUntil('\n');

  tempHold = userOption;

  // once chosen, will begin motor control
  if ( (tempHold.equals("Start")) || (tempHold.equals("start")) )
  {
    Serial.println("Motor control is now accesible. All options are available.");
    delay(3000);

    // starts the motor control aspect of the program and timer
    motorRot = true;
    startMillis = millis();
  }

  // program to control motors only runs once initiated
  while (motorRot != false)
  {
    //codeMillis = millis();           // used to determine the code run-time (uncomment this and the print statements towards the end)
    // this line reads and checks the key input to the serial monitor
    if (Serial.available() > 0)
      userOption = Serial.readStringUntil('\n');
    else
      userHold = true;

    // if tempHold is equal to userOption that means the user enterted the same option userHold will remain true
    if (!tempHold.equals(userOption))
      userHold = false;

    // if timer has passed time limit perform program exit
    if (timeDone == true)
    {
      Serial.println("Time limit passed");
      userOption = "exit";
      userHold = false;
    }

    /*
       this set of lines control the gantry motors
       if the word "up" is sent to the arduino, it will cause the lead screw motors to spin up a certain distance i.e., move tank out of print area
       if the word "down" is sent to the arduino, it will cause the lead screw motors to spin down a certain distance i.e., move tank into print area
       if the word "rotate" is sent to the arduino, it will cause the continuous motor to start spinning
```

```
   if the word "stop" is sent to the arduino, it will cause the continuous motor to stop spinning
   if the word "exit" is sent to the arduino, it will cause the program to stop
   if the word "numbers" is sent to the arduino, it will display all information from the program
   if the word "timer" is sent to the arduino, it will initiate a timer based control for central motor
*/

// sets the option from the user to a new variable to be compared
tempHold = userOption;

if (( (tempHold.equals("Up")) || (tempHold.equals("up")) ) && (userHold != true))
{
  // checks that this method isnt called and gantry already in "up" position
  if (moveUp == 1)
    Serial.println("Gantries already in up position");
  else
  {
    // sets the values to 1 for up and 0 for down
    moveUp = 1;
    moveDown = 0;

    // calls to actually move gantry
    moveGantryMotors(moveUp);
  }
}
else if (( (tempHold.equals("Down")) || (tempHold.equals("down")) ) && (userHold != true))
{
  // checks that this method isnt called and gantry already in "up" position
  if (moveDown == -1)
    Serial.println("Gantries already in down position");
  else
  {
    // sets te value to 0 for up and -1 for down
    moveUp = 0;
    moveDown = -1;

    // calls to actually move gantry
    moveGantryMotors(moveDown);
  }
}
else if (( (tempHold.equals("Rotate")) || (tempHold.equals("rotate")) ) && (userHold != true))
{
  // steady state controls if the continuous motor runs or not
  Serial.println("Continous motor rotating.");

  // sets run millis for correction
  rotateRunMillis = millis();
```

```
      // will start to run
      tempChange = 1;
      steadyState = true;
      accel = true;
    }
    else if (( (tempHold.equals("Stop")) || (tempHold.equals("stop")) ) && (userHold != true))
    {
      // steady state controls if the continuous motor runs or not
      Serial.println("Continuous motor stopping.");

      // sets run millis for correction
      rotateRunMillis = millis();

      // will start to turn off
      tempChange = 1;
      accel = false;
    }
    else if (( (tempHold.equals("Exit")) || (tempHold.equals("exit")) ) && (userHold != true))
    {
      // turns off all options and resets system to end program running anything
      //  if system is up and stopped, just exits program
      Serial.println("Program exiting");

      // if system is down, moves back up
      if (moveDown == -1)
        moveGantryMotors(moveUp);

      // exits out of main program and stops motor spinning
      Serial.println("Good bye");
      motorRot = false;
    }
    else if (( (tempHold.equals("Numbers")) || (tempHold.equals("numbers")) ) && (userHold != true))
    {
      currentMillis = millis();
      elapsed = (currentMillis - startMillis) * 1000;
      contMotorRevs = stepCountCont / 800.0;
      timerMins = Secs / (60000);

      Serial.print("Current continous motor speed (in degrees per second): ");
      Serial.println(DegPerSec);
      Serial.print("Current step delay corresponding to the speed: ");
      Serial.println(stepDelay);
      Serial.print("Current program elapsed time (in seconds): ");
      Serial.println(elapsed);
```

```
      Serial.print("Current continuous motor step count: ");
      Serial.println(stepCountCont);
      Serial.print("Current number of revolutions the continuous motor has spun: ");
      Serial.println(contMotorRevs);
      Serial.print("Current max timer limit (in minutes): ");
      Serial.println(timerMins);

      Serial.println("");
      Serial.println("");
    }
    else if (( (tempHold.equals("Timer")) || (tempHold.equals("timer")) ) && (userHold != true))
    {
      // starts a new timer at the time this option is chosen
      timerMillis = millis();

      // starts option for program to run a check against the timer
      timeCheck = true;
    }

    // if initiated, will turn the continuous motor control to a time based system
    if (timeCheck == true)
    {
      currentMillis = millis();
      elapsedTimeCheck(currentMillis, timerMillis);
    }

    // if initiated and accelerated, will run the central motor
    if ((steadyState == true))
    {
      // calls method to step the motor
      runContMotor();

      // increments step count for this motor
      stepCountCont++;
    }
  }
}
```

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