A Comprehensive Open-Source 3D Printing Ecosystem

This report represents the work of one or more WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on the web without editorial or peer review.
AutoMSLA

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

by
Jacob Arciszewski (CBC)
Jean-Luc Pierre-Louis (CS)
Benjamin Tetreault (ME)
Matthew Plympton (ECE)

Date:
May 2022

Report Submitted to:

Worcester Polytechnic Institute:
Professor Mehul Bhatia, Advisor
Professor Maqsood Ali Mughal, Co-Advisor
Professor Joshua M. Cuneo, Co-Advisor
Professor Shawn C. Burdette, Co-Advisor
Abstract

The AutoMSLA project presents a set of research and instructions required to assemble an MSLA 3D resin printer with automated printing capabilities along with open-source guides to further the 3D resin printing community. The project aims to make improvements for several problems in 3D printing including safety when handling resins, cost barriers, and accessibility. Automation provides a streamlined printing process that does not require human intervention from part printing to curing. Open-source models and code are included for transparency and accessibility. Chemical composition of resins, comprehensive hardware and firmware, as well as models and materials necessary for creation of a working 3D printer are all researched and detailed within this report.
Broader Impacts

The overall goal of the AutoMSLA project is to document all work and research into 3D resin printing in a comprehensive open-source report. The societal impact of this work could be significant if the project is adopted by the open-source community. By automating the printing process, individuals in society might see some health benefits as they needn’t directly handle potentially toxic resins directly to the same extent as before. This is an example of the first fundamental canon in the ASME Code of Ethics of Engineers, “Engineers shall hold paramount to the safety, health and welfare of the public in the performance of their professional duties” [1]. The AutoMSLA project could benefit different groups in society such as students by providing the foundation for group development of the project via open source. It could also further benefit the health of society by allowing for the printer to be used in medical scenarios such as in dentistry to allow for more affordable and practical printing of dental resin products. Overall, by making the printer as affordable as possible and open source, we open the doors to many groups in society to improve both their lives and the lives of those around them through the innovation that is associated with 3D printing.
Acknowledgements

Thank you, Professor Bhatia, Professor Burdette, Professor Cuneo, and Professor Mughal, for acting as our advisors and our consultants, assisting us with both the technical aspects of this project and helping us to navigate through several obstacles with the MQP process, both foreseen and unforeseen. Without your guidance and care, we would not be nearly as far along in this project as we are up to this point.

Thank you, Tinkerbox, for allowing us to become a part of Tinkerbox Cohort 7. Your organization is responsible for providing us with the funding necessary to expand our vision beyond the initial scope of our MQP, as well as giving us several opportunities to grow as both individual innovators and as project team members. The group goal setting and mentorship meetings were instrumental in refining our idea of what we were hoping to accomplish with this project, and in simply helping us to function better as a team.

Thank you, Barbara Fuhrman, for assisting with our component orders and reimbursements. We had around $1000 worth of orders through the ME department alone, including components sourced from overseas. Your time spent helping us order those parts so they would arrive within our tight timeframe for completing this project was instrumental in ensuring our project reached a stage where we could feel confident in what we were presenting.
Table of Contents

Abstract ................................................................................................................................. 3
Broader Impacts .................................................................................................................... 4
Acknowledgements ............................................................................................................. 5
Table of Contents ............................................................................................................... 6
List of Figures ...................................................................................................................... 8
List of Tables ....................................................................................................................... 9
1. Introduction .................................................................................................................. 10
2. Problem & Objective .................................................................................................... 11
3. Background .................................................................................................................... 12
   3.1. History of 3D Printing .............................................................................................. 12
   3.2. How resin 3D Printing Works ................................................................................ 14
   3.4. Existing Large-Scale Resin Printers ....................................................................... 22
4. Methodology .................................................................................................................. 24
   4.1 Printer Design Choice ............................................................................................... 24
   4.2 Components & Budget ............................................................................................. 26
      4.2.1. Extrusions ......................................................................................................... 27
      4.2.2. Printed Parts ...................................................................................................... 27
      4.2.3. Bed Interchange ............................................................................................... 29
      4.2.4. Electronics ........................................................................................................ 31
         4.2.4a. Control Board .............................................................................................. 31
         4.2.4b. Power Supply Unit ....................................................................................... 31
         4.2.4c. Parallel UV Light Array ............................................................................... 32
         4.2.4d. LCD Curing Panel ...................................................................................... 32
         4.2.4e. LCD Display ................................................................................................. 32
         4.2.4f. Boost Converters ......................................................................................... 33
         4.2.4g. Microcomputer ........................................................................................... 33
      4.2.5. Software ............................................................................................................ 36
         4.2.5a. Firmware ...................................................................................................... 36
         4.2.5b. Web Interface ............................................................................................... 37
         4.2.5c. API ................................................................................................................ 37
         4.2.5d. Touchscreen GUI ......................................................................................... 37
4.2.6. Chemicals .................................................................................................................. 38

5. Results .................................................................................................................................. 39
   5.1. Context ............................................................................................................................... 40
   5.2. Hardware/ Physical Components ......................................................................................... 40
   5.3. Electronics .......................................................................................................................... 42
      5.3.1. Power Supplied to Components ................................................................................... 42
   5.4. Software ............................................................................................................................. 43
      5.4.1. Context .......................................................................................................................... 43
      5.4.2. Firmware ....................................................................................................................... 43
      5.4.3. Web Interface ................................................................................................................ 44
      5.4.4. API ............................................................................................................................... 45
      5.4.5. Touchscreen GUI ......................................................................................................... 45
   5.5. Chemicals ......................................................................................................................... 45

References .................................................................................................................................. 48

Appendix A – Assembly Instructions .......................................................................................... 51
Appendix B – Complete Components List .................................................................................. 55
Appendix C – Custom Firmware Code ....................................................................................... 58
Appendix D – Assembly References .......................................................................................... 60
Appendix E - Incomplete Hardware Aspects of Prototype (Future Work) ................................. 65
List of Figures

Figure 1: The Original SLA Printer Invented by Hull [5] ................................................................. 12
Figure 2: Creality Ender-3 Pro [6] (left) and Prusa SL1 [10] (right) .............................................. 13
Figure 3: Graph of Past and Projected North American 3D Printing Market Size [12] ............ 14
Figure 4: Norish type 1 \( \alpha \)-cleavage reaction .................................................................................. 18
Figure 5: Acrylate Monomer Polymerization ................................................................................. 19
Figure 6: Printer Z-axis linear motion assembly .............................................................................. 26
Figure 7: Overhead arm in place below wash bed carrier to catch bed and part ...................... 30
Figure 8: Weighted Scores for Printer MPC from Weighted Decision Matrix ............................ 36
Figure 9: Original Anycubic Photon ............................................................................................. 39
Figure 10: Assembled AutoMSLA Prototype ................................................................................... 40
Figure 11: LAP Radical Generation ................................................................................................. 46
Figure 12: List of hole locations for all extrusions, 1 of 2 (note: subject to change with further work on prototype) ........................................................................................................... 60
Figure 13: List of hole locations for all extrusions, 2 of 2 (note: subject to change with further work on prototype) ........................................................................................................... 61
Figure 14: Locations of Extrusions on Completed Frame Assembly ............................................ 62
Figure 15: Extrusion length and tapping specifications ................................................................. 63
Figure 16: Extrusion hole location specifications ............................................................................. 64
List of Tables

Table 1: Comparison of Existing Large-Scale 3D Resin Printers ................................................. 23
Table 2: Sampling of Available DLP 3D Resin Printers [30] ................................................................. 23
Table 3: Weighted Decision Matrix for Printer Microcomputer ......................................................... 34
Table 4: Data Gathered for MPC Community Support ........................................................................ 35
1. Introduction

The goal of the AutoMSLA project is to develop and provide instructions for the creation of a comprehensive, large-scale, MSLA 3D printing ecosystem. Comprehensive meaning that the printing ecosystem will handle the process of printing the part as well as washing and curing it. Applications of such an ecosystem span from the classroom to a dental office. No such systems are available at the time of writing below $1000 or as commercial offerings. The primary objective is to create an affordable open-source MSLA printer. From there, the focus becomes the additional wash and cure stations, with the final focus being on automation. Finally, clear, and concise instructions are presented for recreation of each part of the ecosystem.
2. Problem & Objective

Our goal for this project is to help resin 3D printing to become as easily accessible to new users/hobbyists as FDM printing is. One main entry barrier to resin printing is the number of extra steps needed after printing is completed. With FDM printing, after the part is printed, the user can remove the part from the bed, pop off supports, and the part is ready to be used. With resin printing, however, the part is not safe to touch until it has been washed and cured, often by hand. This process can be messy and time consuming due to the safety concerns that come with uncured resin, and while external wash & cure stations are commercially available, they still require human intervention to move the printed part over into those separate machines.

Our solution to this problem is to create a large-scale MSLA 3D printing ecosystem capable of automatically printing, washing, and curing prints with little-to-no interaction from the user. At the time of writing, there are no such systems available, and we believe this ecosystem would help remove much of that entry barrier that causes many new 3D printer users to choose FDM over resin printing.
3. Background

3.1. History of 3D Printing

3D printing technology is an application of additive manufacturing in which special materials are used to create objects for use cases such as rapid-prototyping, biomedical applications, and educational applications. Modern 3D printing originated in 1980 when Hideo Kodama invented a printing method that utilized UV exposure and layered mask patterns to harden photo-reactive polymers into solid 3D objects [2]. Kodama patented the technology in 1981 but his ideas were not widely adopted [3]. Not long after, in 1984, Charles Hull invented a stereolithography apparatus (SLA) machine which can be seen in Figure 1 [4]. His machine was like Kodama’s regarding the printing technology. SLA printing also involves using UV light to create 3D objects by building them layer by layer. Hull founded 3D Systems in 1986 and began selling SLA machines in 1988 [4]. These two inventors contributed to both the start of 3D printing and resin printing specifically, which this paper is focused on.

In 1989, Scott and Lisa Crump patented an alternative method of printing, called fused deposition modeling (FDM) or Fused Filament Fabrication (FFF). They would then co-found Stratasys, Inc. to sell FDM printers, taking advantage of their patent which expired 20 years later in 2009. Around which time, the average price of an FDM printer dropped from $10,000 to
under $1,000 [2]. The price drop contributed to the increased accessibility of FDM printers for the average consumer. Popular printers such as the Creality Ender 3 Pro offer capable printing at prices as low as $250 and even lower, at the time of writing [6], [7]. FDM printers use plastic filament instead of photopolymer resins and do not rely on UV exposure. The FDM market has also developed a strong open-source community with many open-source printers available ranging from low to high end, the Ender 3 being included [8]. On the other hand, the resin printing market has not developed as strongly, as may be noticeable from the lack of resin printers in list of open-source 3D printers [9]. The only viable offering for open-source resin printers included by Lucas Carolo in his 2021 list is the Prusa SL1 [8]. Both the Ender 3 Pro and Prusa SL1 can be seen in Figure 2.

![Creality Ender-3 Pro (left) and Prusa SL1 (right)](image)

Figure 2: Creality Ender-3 Pro [6] (left) and Prusa SL1 [10] (right)

The Prusa SL1 is a masked stereolithography (MSLA) printer released in 2018 with a 5.5 inch, 1440p display at a price range of $1300 to $1600 [10]. MSLA is related to SLA as the name suggests. The main difference between the technologies is the method of UV curing. The original SLA invented by Charles Hull is also referred to as laser-based SLA, because it uses lasers as a light source [11]. Whereas MSLA uses an LED array combined with an LCD.
photomask [11]. It is worth noting that there is a third main category of SLA based printing, called digital light processing stereolithography (DLP-SLA) which uses a digital projector as the light source [11]. These three printing processes are united under the SLA banner and all three use “a vat of photo-reactive liquid resin” that is “selectively exposed to light in order to form very thin solid layers that stack up to create one solid object” [11].

![North America 3D Printing market size, by technology, 2017 - 2028 (USD Billion)](image)

*Figure 3: Graph of Past and Projected North American 3D Printing Market Size [12]*

FDM based printing and SLA based printing are the two main types of printing used by hobbyists. However, this project will focus solely on SLA printing, specifically MSLA printing. Despite comprising much of the market share for 3D printers, as can be seen in Figure 3, SLA printing lacks a strong open-source community. This paper aims to resolve that by presenting an affordable and easy to use printer which will be positioned competitively in the market.

**3.2. How resin 3D Printing Works**

As was briefly mentioned in the previous section, there are a wide variety of existing additive manufacturing techniques. Most commonly resin printing refers to printing techniques that utilize a UV curing resin in conjunction with some type of controlled UV light source. The
specifics of the light source and how layers are shaped are the primary differentiating factors between different resin printing processes. This paper is centered around the creation of an MSLA printer, so the process described here will not apply in full to other resin processes.

MSLA printing is a layer-based process much like the well-known FDM process. In short, the resin is stored in a vat and cured in layers shaped by a software slicer to build up the desired part geometry one layer at a time. There are two primary differences in the utilization of this layer-stacking process between FDM and MSLA processes: The way each layer is built, and the orientation parts are printed in.

FDM relies on a moving extruder to draw each layer as a series of lines while melting and depositing plastic. Tangentially, this is similar to standard SLA printing in which a high-power UV laser is used to draw out each layer in the same fashion. MSLA instead uses a standard LCD screen located just below the clear bottom of the resin vat to display a negative image of each layer as they are exposed. This allows the use of a UV light source that illuminates the entire build area of the printer because all areas of the vat not included in a layer are blocked from exposure by the blacked-out LCD. This does mean that the maximum theoretical print quality of an MSLA printer is inherently limited by the pixel density of the masking screen used, but the numerous benefits of this combination of flooded light source and masking screen outweigh this negative in many cases. By using a flooded light source, the entire area of each layer is exposed at once. This means that the time a print takes on an MSLA printer is only geometrically dependent on the height of the parts: Each layer takes a set time to print regardless of how much area on the bed is being exposed, so adding more parts of equal or shorter height will not increase print time. Additionally, the stack of a light source and masking screen requires no moving parts to operate which makes MSLA printers extremely mechanically simple and
very affordable as a result. Masking screens can be replaced with relative ease when they burn out as they are typically only adhered in place with tape, and the only motion axis that must be maintained on a basic MSLA printer is the Z axis.

As mentioned, the second primary difference between MSLA and FDM is the orientation of the layer stack: MSLA printers typically suspend the build plate upside down over the print area while still printing the bottom layer first and working upwards, building the part upside down. This orientation difference most prominently changes which type of support structure is most appropriate. FDM printers use large support grids or zig-zags to build relatively solid blocks under any part geometry with steep overhangs, while resin printers use tree-like support towers to attach part geometry that would otherwise not be attached to the in-progress part to the build plate. This means that less material is used up printing supports, but also means that the process of optimizing part orientation and support specifications in the slicer must be entirely relearned if a user is accustomed to FDM slicing.

An additional distinction between FDM printing and all resin printing processes is in material handling. FDM prints are complete and safe to handle straight off the build plate, with the only typical post processing being the removal of supports. Resin prints come off of the printer in a partially cured state where they are still relatively fragile and unsafe to handle without gloves. Uncured resin must be washed off the part before it is exposed entirely to UV light for a period of time to fully cure the resin. Support structures can be removed before or after the post-cure, and the part is safe to handle without PPE after the post cure.

Cumulatively, the complete printing process in a basic MSLA printer is typically as follows:
1. The build plate is leveled relative to the screen to ensure the part will adhere to the build plate properly.

2. A vat with a FEP bottom is placed over the screen and filled partially with resin.

3. The print is started, and the Z-axis lowers the build plate until it is one layer height away from the screen. This leaves a single-layer thick resin space between the screen and build plate.

4. The masking screen displays the negative image of the layer, and the UV light is switched on for the slicer-determined exposure time to cure the layer.

5. The build plate is gently lifted away from the FEP to peel apart the suction force between the cured layer and the screen leaving the cured layer attached to the build plate.

6. The build plate is lowered to one layer height above the last exposure height.

7. The exposure, peel, and reset processes repeat for the duration of the print.

8. The finished print is removed from the build plate and post processed.

3.3. MSLA Printing Resins

The focus of this project revolves around 3D resin printing, therefore, understanding the resins available to print with is also vital. Masked Stereolithography (MSLA) printing resins are all based on photopolymer resins [13]. The process by which MSLA printers cure liquid resins into solid materials revolves around ultraviolet light activating a photosensitive molecule to begin a chain reaction of monomer and oligomer polymerization. The photo initiator molecules involved in MSLA printing irradiate and release a free radical when exposed to light at a wavelength of 385-405nm [13]. These photoinitiator molecules work via a process called a Norish type 1 $\alpha$-cleavage reaction [14]. This reaction occurs when ultraviolet light attacks the...
functional group bond of a ketone, cleaving that bond, and leaving a free radical electron on both the functional group and the cleaved carbon. This is shown in the figure below.

![Figure 4: Norish type 1 \( \alpha \)-cleavage reaction](image)

This diagram shows a ketone group attacked by heat energy. The ketone then goes through a series of transitional states until the cleavage occurs and leaves the functional group as well as the ketone group with free radical electrons [14].

Following the Norish type 1 \( \alpha \)-cleavage reaction, both free radical groups from the photoinitiator can attack the exposed carbon of an acrylate group, transitioning the free radical electron onto the acrylate monomer or oligomer. The acrylate group with a free radical can then interact with another acrylate group with a free radical to form a bond between both monomers/oligomers, thus causing the polymerization effect to occur. This radical polymerization reaction is depicted by the figure below.
Figure 5: Acrylate Monomer Polymerization

This figure depicts a free radical group attacking an exposed carbon of an acrylate group. The free radical is then transferred to a transitional state of the acrylate group until this radical can form a bond with another acrylate group. This chain reaction is the foundation for acrylate polymerization [15].

By this process, the liquid resin is polymerized into a solid plastic which is the product of the 3D print. Examples of these photo initiator molecules include Lithium phenyl (2,4,6-trimethylbenzoyl) phosphinate (LAP) and diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO) [16]. The free radical molecule produced by the photo initiators activates polymerization and crosslinking of the resin monomer and oligomer functional groups. Methacrylate and diacrylate based molecules are ideal for 3D print resins as the primary structural polymer due to their ability to accept a free radical and begin a chain reaction of crosslinking [17]. 3D MSLA
print resins include these core components of the photo initiator and reactive monomer/oligomer, however additional materials and post print coatings can be added to diversify resin features and applications. Categories of common resin types include standard resins, clear resins, flexible resins, and dental resins [18] [19]. Standard resins are a common hobbyist 3D printing resin composed of methacrylate monomers and oligomers, a photo initiator, and a colored dye. The main applications of standard resins are small to medium sized parts, toys, or figures. Clear resins are similar in composition and application to standard resins; however, they do not include a colored dye. Flexible resin chemical composition differs slightly from standard and clear resins. Flexible resins are acrylate based however they rely on molecules such as aliphatic urethane di-acrylate (AUD) and epoxy aliphatic acrylate (EAA) for the stretch and flexibility of prints [20]. These flexible resins prints can stretch upwards of >1000% their original form and can be used in the printing of grippers, soft actuators, and balloons [21]. Dental resins are imperative to the dental and orthodontic community. They can be used in several ways such as prosthodontics, oral and maxillofacial surgery, and general orthodontics. These resins are acrylic based, however the additives to these resins are what makes them unique. Due to this wide range of applications the resins utilized in dentistry have additional molecules added to fit the desired purpose of the resin. Although features of dental resins can range according to their specific composition and function, one common factor among them is their biocompatibility [19]. This biocompatibility is especially important for dental resins since they often are in contact with a person’s mouth. Although all these resins have differing functions and chemical compositions, 3D printers can utilize and print using each.

The biocompatibility of dental resins allows these prints to be safe for humans as well as resistant to bacterial and microbial infections. One key element of bacterial resistance for resins
is the ability of the resin to combat biofilm growth. Bacterial biofilms are communities of many bacterial cells encased together via an extracellular matrix produced by the community of bacteria cells [22]. These biofilms naturally occur for many bacterial species, increase the bacterial colonies' resistances due to the extracellular matrix, and importantly can lead to infections [23]. To combat this form of bacterial growth dental resins, as well as other biocompatible resins, are combined with antimicrobial components. One of which is silver nanoparticles. Silver ions are an effective antimicrobial due to the ability of these ions to reduce bacterial membrane function. Silver (I) ions can form bonds on DNA and thiol groups of bacterial proteins which in turn affect the replication process of the Ag linked DNA [24]. Against bacteria, silver ion nanoparticles can inhibit the bacterial membrane by disrupting the permeability as well as inhibiting metabolic proteins and enzymes [23]. Furthermore, toxicity to humans is mitigated by the low concentration of the silver nanoparticles. Various other metal ions such as copper and zinc oxide have also been used in conjunction with biocompatible resins to combat bacterial growth. However, bacterial resistance such as flagellin of Gram-negative bacteria can accumulate silver nanoparticles away from the bacteria reducing the effect of the silver ions [23]. Since silver and other metal ions in high concentrations can be harmful to humans, as well as resisted by some forms of bacteria, alternative methods can be used.

Antimicrobial polymeric resins are another form of bacterial resistance resins can have. These resin components can be in the form of various polymerizable materials, which affect various aspects of bacteria. Many antimicrobial polymeric resins interact due to the negatively charged phospholipids of bacterial membranes such as phosphatidylglycerol [23]. An example of an antimicrobial polymeric is an imidazole derivative aromatic polymer-based resin. These imidazole polymers utilize their heterocyclic nature along with positive charges to disrupt and
destroy the negatively charged bacterial cell wall or cytoplasm, like silver ions [25], [26].
Additionally, antimicrobial peptides are another class of polymeric which can resist bacteria. These peptides are derived from peptides that evolved out of the human immune system. Due to this fact, they can be used to selectively target bacteria cells while avoiding human mammalian cells. Again, the negative charge of bacterial membranes as opposed to the neutral charge of mammalian membranes allows antimicrobial peptides to be electrostatically attracted to bacteria. These peptides, once attracted to a membrane, use hydrophobic portions to integrate and form a pore in the membrane. This pore then allows the release of bacterial substances eventually leading to the death of the cell [23].

3.4. Existing Large-Scale Resin Printers

In this section we briefly cover the currently available sampling of medium to large-scale 3D resin printers, starting from printers with a minimum screen size of 8.9”. Table 1 contains a list of various large resin printer offerings, increasing in screen size, except for the three SLA printers which use lasers instead of screens [27] [28] [29]. One trend noticeable in the table is that of price. The printers generally increase in price as they increase in size. There are generally not any affordable large-scale resin printers at 10.1” or above, with the exception being the Qidi Tech S-Box, which was not in-stock for purchase at the time of writing. It is also worth noting the methods used for the printers. Most of the printers use some form of SLA, with the majority using MSLA.

<table>
<thead>
<tr>
<th>Name</th>
<th>Screen Size (in.)</th>
<th>Resolution</th>
<th>Max. Build Volume (mm)</th>
<th>Method</th>
<th>Price ($USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elegoo Saturn</td>
<td>8.9”</td>
<td>4K mono-LCD</td>
<td>192 x 120 x 200</td>
<td>MSLA</td>
<td>$500</td>
</tr>
<tr>
<td>Anycubic Photon Mono X</td>
<td>8.9”</td>
<td>4K mono-LCD</td>
<td>192 x 120 x 245</td>
<td>MSLA</td>
<td>$540</td>
</tr>
</tbody>
</table>
Table 1: Comparison of Existing Large-Scale 3D Resin Printers

<table>
<thead>
<tr>
<th>Name</th>
<th>Screen Size (in.)</th>
<th>Resolution</th>
<th>Max. Build Volume (mm)</th>
<th>Method</th>
<th>Price ($USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epax E10 Mono</td>
<td>8.9&quot;</td>
<td>4K mono-LCD</td>
<td>192 x 120 x 250</td>
<td>MSLA</td>
<td>$699</td>
</tr>
<tr>
<td>Uniz Slash 2 Plus</td>
<td>8.9&quot;</td>
<td>4K LCD</td>
<td>192 x 120 x 200</td>
<td>MSLA</td>
<td>$3,599</td>
</tr>
<tr>
<td>Phrozen Sonic Mighty 4K</td>
<td>9.3&quot;</td>
<td>4K mono-LCD</td>
<td>200 x 125 x 220</td>
<td>MSLA</td>
<td>$599</td>
</tr>
<tr>
<td>Qidi Tech S-Box</td>
<td>10.1&quot;</td>
<td>2K LCD</td>
<td>215 x 130 x 200</td>
<td>MSLA</td>
<td>$529</td>
</tr>
<tr>
<td>Wiiboox Light 280</td>
<td>10.1&quot;</td>
<td>5K mono-LCD</td>
<td>215 x 135 x 280</td>
<td>MSLA</td>
<td>$2,599</td>
</tr>
<tr>
<td>Peopoly Phenom Prime</td>
<td>12.5&quot;</td>
<td>5.5K mono-LCD</td>
<td>275 x 155 x 400</td>
<td>MSLA</td>
<td>$2,799</td>
</tr>
<tr>
<td>Elegoo Jupiter</td>
<td>12.8&quot;</td>
<td>6K LCD</td>
<td>277 x 156 x 300</td>
<td>MSLA</td>
<td>$1,300</td>
</tr>
<tr>
<td>Phrozen Transform</td>
<td>13.3&quot;</td>
<td>4K mono-LCD</td>
<td>290 x 160 x 400</td>
<td>MSLA</td>
<td>$1,999</td>
</tr>
<tr>
<td>Phrozen Sonic Mega 8K</td>
<td>15&quot;</td>
<td>8K LCD</td>
<td>330 x 185 x 400</td>
<td>MSLA</td>
<td>$1,699</td>
</tr>
<tr>
<td>Photocentric Liquid Crystal Magna</td>
<td>23&quot;</td>
<td>4K LCD</td>
<td>510 x 280 x 350</td>
<td>MSLA</td>
<td>$19,500</td>
</tr>
<tr>
<td>Formlabs Form 3L</td>
<td>N/A</td>
<td>N/A</td>
<td>335 x 200 x 300</td>
<td>LFS</td>
<td>$10,999</td>
</tr>
<tr>
<td>3D Systems ProX 950</td>
<td>N/A</td>
<td>N/A</td>
<td>1500 x 750 x 550</td>
<td>SLA</td>
<td>$250,000</td>
</tr>
<tr>
<td>UnionTech RSPro800</td>
<td>N/A</td>
<td>N/A</td>
<td>800 x 800 x 550</td>
<td>SLA</td>
<td>$100,000-$250,000</td>
</tr>
<tr>
<td>DWS X Pro S</td>
<td>N/A</td>
<td>N/A</td>
<td>300 x 300 x 300</td>
<td>SLA</td>
<td>$50,000-$100,000</td>
</tr>
</tbody>
</table>

Table 2: Sampling of Available DLP 3D Resin Printers [30]

<table>
<thead>
<tr>
<th>Name</th>
<th>Screen Size (in.)</th>
<th>Resolution</th>
<th>Max. Build Volume (mm)</th>
<th>Method</th>
<th>Price ($USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Systems ProX 950</td>
<td>15&quot;</td>
<td></td>
<td></td>
<td></td>
<td>$250,000</td>
</tr>
</tbody>
</table>

Comparing Table 1 to Table 2 highlights part of the reason why MSLA is far more prevalent, cost. Comparable DLP printers of much smaller size cost significantly more due to the differences in technology. This is indicative of the fact that DLP printing technology has not reached the stage of being affordable for consumers, unlike for MSLA and FDM.

At the time of writing, the most comparable commercially available unit is the Elegoo Jupiter which can be seen in Table 1. It is also worth noting that the price of the Jupiter is for a
printer only and does not include wash and cure units or any type of integration between the printer and post processing units.

4. Methodology

4.1 Printer Design Choice

As stated in our objective statement, the intent was to create a large-format MSLA printer with integrated automated post-processing solutions. Such a printer would be useful to hobbyist and maker users who would likely be unable to afford a printer large or a matching, standalone post-processing system to accompany it. Based on this intended user base, the machine was designed with an emphasis on using cost-effective and accessible materials, being simple to assemble and calibrate, and being easy to diagnose and repair when difficulties arise. The overarching goal is to produce sufficiently thorough documentation such that the average tinkerer can source a parts kit and assemble the printer with basic tools and knowledge, much like a DIY FDM printer kit.

The simplicity of the MSLA process and printer hardware is what initially motivated the selection of the process. By nature, there is extremely few required major components and systems required to perform the MSLA process. In its most simple form, a MSLA printer consists of a masking screen, UV light source, resin vat, build plate, Z-axis, control board, and firmware. Design simplification was paramount to retaining the accessible nature of the printer, and so all attempts were made to avoid lengthening this list needlessly. The only major addition made to the printer beyond this simple form is the inclusion of a tilt axis like that seen in Prusa’s SL1 and SL1S printers. This mechanism introduces a rotation axis along the long edge of the screen and tilts the screen, FEP, and vat stack away from the build plate to break the suction force more gradually than the simpler alternative; Most existing MSLA printers pull directly
normal to the adhered surfaces by raising the Z axis to break this suction force. The tilt mechanism was chosen out of concerns over the relatively high maximum possible suction forces inherent to a large print area and further justified because it can also be used to significantly increase print speed. By peeling the FEP away at an angle rather than pulling the Z-axis directly up after curing a layer, the forces seen in separating the bond between the FEP are better distributed and the chances of print failure caused by a layer remaining on the FEP are decreased significantly.

The addition of automated post-processing required the creation of an integrated system of motion axes much like the systems used on FDM printers. Four vertical axes make up the Z-axis and part-processing stations of the system, and a fifth horizontal axis is included to move parts between these stations. A sixth motion axis exists in the tilt mechanism for the screen carrier, and a seventh, revolute axis operates the curing turntable.

The printer Z-axis is the most robust and costly axis as it is a crucial component in facilitating high print quality. It utilizes a T8 lead screw directly coupled to the Z stepper motor to drive motion. Two, opposing rails are used to ensure the bed remains rigid against the peel forces and to aid in squaring the Z-axis and bed to the frame. The lead screw interfaces with an anti-backlash nut mounted to the bed arm and runs between the two rails and bed. This combination ensures tight repeatability, sufficient granular control, and hobby-friendly servicing and maintenance without being cost prohibitive. Lower quality but still adequately precise linear rails can be sourced very cheaply and readily now thanks to their emerging prevalence in FDM printers.
All the other motion axes have much lower precision requirements, and as such linear rails and leadscrews would be needlessly expensive. Instead, these axes are driven with commonly available 10mm wide GT2 timing belts and stepper motors, and motion rides on V-slot bearing rollers. V slot rollers offer more than adequate positional and motion consistency for the wash, cure, and part interchange axes, are readily available due to their prevalence in affordable FDM printers, are very affordable, and are very easy to assemble with low maintenance. The three vertical axes that implement this motion arrangement make up the two wash stations and the cure station. Two wash stations are included to allow for the automated selection of a water or alcohol wash bath to account for most common types of resin. The final V-slot roller axis is the horizontal axis that moves parts between the stations, and the use of the V-slot system was a key factor in permitting for its length of more than 2m within the budget constraints of this project.

4.2 Components & Budget
This section is focused on detailing the purpose of each selected component and our reasons for selecting it. A full list of our components and associated costs can be found in Appendix B.

4.2.1. Extrusions

As described in section 4.1 above, V-slot rollers were selected for most of the motion axes. This contributed to the selection of standard 5 series base 20 aluminum extrusions as the frame material, as did several other factors: Aluminum extrusions are ubiquitous and can be sourced in most any market worldwide. They can often be purchased cut to length, and these CNC cuts are accurate enough to enable the use of “blind joints” to construct the frame. Blind joints use a flanged head screw to attach two extrusions perpendicularly with only a single fastener by threading the internal hole of the extrusion at its end and threading the screw into this. The flanged head can seat in the slot of the extrusion to be mated with the threaded extrusion facing outwards perpendicularly from the extrusion. These joints are extremely strong despite their simplicity, and the use of the slot profile and internal hole mean that they consistently produce very near-square joints with factory-cut extrusions. Additionally, the T-slot profile enables every location on every frame piece to be used for mounting by use of T-nuts. The combination of the simplicity of blind joints and the flexible nature of the T-slot system made aluminum extrusions the clear solution for building the machine frame.

4.2.2. Printed Parts

Once again, the intended user base of makers and hobbyists motivated the decision to use FDM printing as a primary manufacturing technique in making the parts for the AutoMSLA. The FDM printing process enabled very rapid prototyping and provisioning to facilitate fast development of the design, but also produces components that are sufficiently strong and
dimensionally accurate for use in the printer. All components can be printed from PLA on an Ender 3 sized printer, meaning that even the most budget of printing setups are likely able to print an entire part set for the AutoMSLA.

A consistent trend across the affordable (and professional) resin printers currently on the market is the used of one-piece machined aluminum components for build plates and resin vats. While WPI’s manufacturing facilities would allow for these approaches to be replicated, requiring the use of an adequately sized mill and including the cost of material would significantly harm the accessibility of the printer to hobbyists and makers. Instead, the build plate is FDM printed in two parts that are glued together around an electromagnet before the print bed surface face is flattened on an aluminum tooling plate. The actual print surface is a spring steel sheet much like those becoming a popular aftermarket upgrade for hobby resin printers affixed via the embedded electromagnet. The resin vat required a more complex approach as it must remain flat when the FEP is tensioned across it and not allow resin to permeate or otherwise leak through it when filled with liquid resin for extended periods of time. Because an order of aluminum extrusions is already required, the chosen solution was to utilize a different standard profile to make an aluminum vat without machining. The vat is composed of a blind-jointed rectangle of 2040 extrusions that each have one smooth side, facing inwards. An FDM printed frame affixed to the bottom of the extrusions accommodates for a gasket that seals the ring to the extrusions and a boss for the FEP tensioning rings to reside. The FEP rings are screwed through the plastic frame into standard T nuts in the extrusions to ensure the tension remains consistent. An additional benefit to this accessibility-optimized vat construction is the low cost of construction. Notably, this allows for several vats to be constructed and stored with frequently
used resins in them to facilitate quickly changing between materials by simply interchanging the vat and wiping the bed.

Most of the printed components include several heat-set inserts. These are brass inserts typically used in injection molding that can be pressed into holes in FDM printed parts and sheet acrylic to permanently add metal threads to the plastic holes. Alongside aluminum extrusions and FDM printed parts, the third primary material used is sheet acrylic. Acrylic is available in translucent tints that block UV light while still being visibly transparent, and so it is optimal for the upper enclosure of the printer. It is also used for the lower enclosure panels because of its cost, availability, ability to be laser cut, and compatibility with these heat-set inserts. Due to time constraints and scattered availability, only clear acrylic could be sourced for the construction of the prototype. To compensate, a tinting film that blocks nearly all UV was found and used to tint the upper windows of the enclosure. The remaining panels were wrapped in black permanent adhesive vinyl to prevent UV light leakage and conceal the electronics. These films make wrapping clear acrylic an affordable alternative to purchasing opaque and UV-blocking material in instances where these more specialized sheets are harder to source.

4.2.3. Bed Interchange

To allow for automation of the post-processing steps, a method to automatically remove parts from the printer and move them elsewhere had to be devised. To avoid complications caused by trying to interface with constantly changing part geometry, it was decided that parts would remain attached to the build plate the entire time they are in the machine. This is enabled by using spring steel sheets as the build surface by attaching them to build plate carriers electromagnetically. The electromagnets are embedded inside the printed bed carriers and are switched as necessary for part transfer by the custom firmware. The spring steel sheets make for
an affordable build surface and as a bonus can be flexed to remove particularly stubborn or fragile parts.

With a method of removing the part from the printer, a process to move the part through post-processing steps is required. This is done by use of the horizontal overhead axis which is aligned along the depth of the printer with the build plates. When moving a build plate, the hook-shaped arm attached to this axis is moved under the edges of the build plate before the electromagnet is released. This leaves the build plate simply sitting on top of the horizontal effector supported around three of its edges.

![Figure 7: Overhead arm in place below wash bed carrier to catch bed and part](image)

The plate can then be moved along horizontally to the next station where the next bed carrier will lower and attach to the plate magnetically. The plate is lifted, and the effector is moved back to its clearance location off the side of the printer. This system avoids complication by relying on gravity to “attach” the plate to the horizontal axis to make the embedded electromagnets the only active components in the bed holding systems.
4.2.4. Electronics

This section covers the electronics selected for the system. This includes the printer control board, power supply, UV lights, LCD screens, boost converters, and an auxiliary microcomputer.

4.2.4a. Control Board

For our printer’s control board, we decided to go with the BTT Octopus V1.1 Control Board from Banggood, which costs $46.99. The control board is responsible for taking inputs of our code and translating it to commands for the rest of the printer’s mechanical/electronic components. It is also responsible for powering the microcontroller and motor drivers. This specific control board was chosen for our prototype because it has a wide array of different ports for many different uses. It has much more broad use than we would need, but having that flexibility allowed us to ensure there was no functionality missing, and we would be able to come to a decision on a cheaper & more specialized control board for our final printer. This control board takes a 24V input, which is supplied by our SHNITPWR power supply.

4.2.4b. Power Supply Unit

To power all our different components, we decided to purchase two separate power supplies. First, to power our BTT mainboard, we went with the SHNITPWR 24V DC External Power Supply Unit from Amazon, which costs $20.99/unit. Since this PSU supplies 120W @ 24V, this will meet our 24V input requirement for the board while supplying enough wattage to successfully power the board, and in turn the Raspberry Pi, fans, and all motor drivers. For our second PSU, we chose the Mean Well LRS-200-12 Switching Power Supply from Amazon, which costs $26.95/unit. This unit supplies 200W @ 12V, which we boosted to 24V using a boost converter to meet the input voltage for the LED driver board. This board then boosted the
voltage to 55V, which was the required input for the UV Array. This 12V power supply will also be used to power the 12V input LCD masking screen and the 12V input electromagnets we are using to pass the build plate from rail to rail.

4.2.4c. Parallel UV Light Array

The 10.1” UVA-S64 High Power UV LED Module from Alibaba, which costs $135/unit, was selected as our printer’s UV Light Array. This array is responsible for providing light to be filtered in the print bed by our LCD Curing Panel. We chose this specific UV array because it is very affordable compared to many other UV Arrays of comparable size class. As was mentioned in section 4.2.4b, this component requires a 55V input, so as mentioned we fed a 24V input to the included driver board and the driver board boosted that 24V input to 55V.

4.2.4d. LCD Curing Panel

To go along with our UV Light Array, we selected the 10.1” RV101FBB-N00 5K Monochrome LCD Display from Alibaba, which costs $240/unit. This LCD panel will be responsible for filtering light from the UV array into much more precise shapes that will be cured layer by layer. We chose this panel because its resolution is high end, while it is still very affordable for its size class. This component requires a 12V input voltage, which is supplied by our Mean Well PSU.

4.2.4e. LCD Display

We selected a 7” LCD Display Screen from DigiKey for our touch screen display. This component will be the actual touch screen the user interacts with on the front of the printer. Here they will be able to control certain settings and monitor the state of their current print. This specific panel was chosen because it was affordable and fairly large compared to other display
screens. We also wanted to choose a touch screen to allow for greater ease of use and simpler controls for new users/hobbyists. This display will be powered by our 12V Mean Well PSU.

4.2.4f. Boost Converters

To ensure our printer components all receive their specified input voltages, and to ensure their input currents are within the acceptable range, we decided to use AITRIP DC 400W 15A Step-up Boost Converters from Amazon, which cost $7.15/unit. These can take a signal with a lower voltage with higher current and convert it to a signal with higher voltage and lower current. The power supplied will always remain about the same, as losses in DC-DC converters are often very small. We only needed to use one of these boost converters to boost our Mean Well PSU’s 12V output to the required 24V input for the LED driver board.

4.2.4g. Microcomputer

For the microcomputer (MPC) we selected the Raspberry Pi 4 Model B. The Raspberry Pi is responsible for hosting the web interface which allows for remotely accessing the printer. To assist with MPC selection, a weighted decision matrix was created using subjective qualitative scores for various MPC brands. The brands are numbered to save space, including:

- 1: Raspberry Pi
- 2: Arduino
- 3: NVIDIA Jetson
- 4: BeagleBone and Texas Instruments
- 5: STM32
- 6: ESP32
- 7: Khadas.
The decision matrix, which can be seen in Table 3, is color coded to highlight the relative scores of each MPC. The color scale transitions from red (indicating low-scoring) to yellow to green (indicating high-scoring), like a traffic light.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affordability</td>
<td>25%</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Availability</td>
<td>25%</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Performance</td>
<td>20%</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Community Support</td>
<td>25%</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td>5%</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

| Weighted Project Scores | 100%  | 2.75 | 2.45 | 1.65 | 1.95 | 2.5 | 2.35 | 1.75 |

Table 3: Weighted Decision Matrix for Printer Microcomputer

The criteria used for selecting the MPC attempts to take into consideration the most important aspects for a hobbyist. The categories are determined as:

- **Affordability** is a measure of how affordable the computers are. Scores of 3 were given for those sold for $40 or less, 2 for $40-$80, and 3 for $80+.

- **Availability** is a measure of how easy it is to procure the computers. A score of 3 was given to those found on 7-9 of the websites considered, 2 for those found on 4-6, and 1 for those found on 1-3. The websites considered were Amazon, Best Buy, Walmart, Microcenter, Adafruit, DigiKey, Mouser, and Newegg. The websites were selected to provide a sampling of general, specialized, and hobbyist tech retailers.

- **Performance** is a measure of how much compute power each computer has. Higher-end computers with more processing power were given a 3, while low-level computers were given a 1.
• Community support is a measure of how strong of an online community the brand has.

The scores for community support were determined using results from a Google search containing the name of the brand and the word “forum” (i.e., “Raspberry Pi Forum”). The results found at the time of writing can be found in Table 4. A score of 3 was given for those with the most combined results and a score of 2 was given for the least results.

• Wireless connectivity is an indication of whether the computers has built in wireless connectivity. A score of 3 was given for wireless support and a score of 1 was given for a lack of wireless support.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td># Forums (Unique)</td>
<td>15</td>
<td>11</td>
<td>1</td>
<td>15</td>
<td>13</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td># Forums (Total)</td>
<td>17</td>
<td>15</td>
<td>18</td>
<td>16</td>
<td>18</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td># Results (Total)</td>
<td>24,500,000</td>
<td>18,400,000</td>
<td>352,000</td>
<td>423,000</td>
<td>2,400,000</td>
<td>3,380,000</td>
<td>260,000</td>
</tr>
</tbody>
</table>

*Table 4: Data Gathered for MPC Community Support*

The result of the decision matrix can be seen as visualized in Error! Reference source not found.. The Raspberry Pi is a clear winner with a weighted score of 2.75, which is why we selected it for this printer.
4.2.5. Software

When researching the software required to run a 3D printer, we found two main parts: the firmware and web interface. The firmware is run on the printer’s control board and is the only software required to run the printer. It handles the kinematics of printing by controlling the electronics via interfaces on the control board. 3D Printer firmware uses G-Code as the primary language for interaction with the printer electronics and hardware, as is common for CNC machines. Web interfaces serve to make printers “smarter” by connecting a more powerful computer such as a Raspberry Pi to the control board. The web interface allows for smart features such as remote monitoring and controlling of the printer.

4.2.5a. Firmware

When selecting firmware for the printer, we had to consider compatibility with the selected control board. The only firmware options that are officially listed as supported by BIGTREETECH, the manufacturer of the control board, are Marlin, Klipper, and RepRap [31].
We also found that forks of those three are potentially viable options as is the case with RatOS which claims to officially support the BIGTREETECH Octopus V1.1 [32]. We selected Klipper as our firmware due to several reasons including: a robust feature-set, high speed printing, web-interface compatibility, precision movement, and robust documentation. These aspects combined with the fact that it is designed to run with a Raspberry Pi and is open source, mean that it should both work well for the printer and be easy to modify.

4.2.5b. Web Interface

Unlike with firmware, there is a far greater selection of web interface software for resin printers. Most web interfaces are designed to run on more powerful general-purpose computers such as a Raspberry Pi or a Windows PC. It is important still to ensure compatibility between the selected software options. In the case of MSLA printing, the web interface also often serves as part of the firmware by sending G-code to the control board and displaying the relevant masking images on the masking screen. For the web interface we will use Photonic3D due to its robust feature set, which includes a slicer so that we do not need separate software to slice 3D models into the necessary layers and masks for printing. Photonic3D is open-source and available on GitHub [33].

4.2.5c. API

To allow other programs to communicate with Klipper, we will use Moonraker which exposes printer status and methods via a Python 3 based web server [32]. Moonraker is open-source and available on GitHub [34].

4.2.5d. Touchscreen GUI

The final piece of software needed is that which shows the GUI on the touchscreen attached to the printer. For this we’ve selected Klipperscreen which is a “touchscreen GUI that
interfaces with Klipper via Moonraker” [35]. Klipperscreen is open-source and available on GitHub [35].

4.2.6. Chemicals

The chemicals purchased for this project included components necessary to create a standard 3D print resin. Butyl Methacrylate purchased from TCI America™ and Isobutyl methacrylate purchased from Thermo Scientific™ served as the acrylate base of the resin. These chemicals were chosen for their methacrylate properties and the interaction they will be able to have with free radicals created from a photo initiator. Diphenyl(2,4,6-trimethylbenzoyl)phosphine Oxide purchased from TCI America™ was chosen as the photo initiator for this resin. The final component to this resin is Bis(2-butoxyethyl) Adipate purchased from TCI America™. This chemical is a plasticizer and was added to the resin components for its ability to support polymer chains increasing final print stability and reduce the brittleness of cured resin prints. Each of these chemicals were mixed into one solution which would act as the resin for 3D printing. To calculate the correct concentrations of each chemical, percentage by weight calculations were made for each substituent. The desired concentrations were based off SDS and chemical makeups of other on market resins. The percentages used for the creation of the resin were 20% by weight Isobutyl Methacrylate, 35% by weight Butyl Methacrylate, 5% Diphenyl (2,4,6-trimethyl benzyl) phosphine oxide, and 40% by weight Bis (2-butoxyethyl) Adipate. Once the calculated amounts of each chemical were weighted and combined into a 500 mL UV resistant bottle, the solution was vigorously swirled to ensure homogeneity. The resin solution once well mixed, was added to the empty vat of an original Anycubic Photon 3D resin printer and set to run at the specifications below.
This figure shows two print settings for the Original Anycubic Photon printer which was used to test the resins our team created. The left side screenshot shows the settings used when testing the resin whereas the right-side screenshot shows default settings for perspective. We decided to increase the exposure time, as well as the bottom exposure time to ensure that the photoinitiator in our resin had time to radicalize and facilitate polymerization.

5. Results
5.1. Context

The MQP suffered setbacks due to several factors which limited the team’s ability to produce a functional printer as originally intended. These limitations came primarily from significant delays in necessary part delivery. As a result, most parts required were not obtained until April, severely limiting the time given to build the printer. Furthermore, not all the parts required for the printer arrived before the end of the project and some parts were not able to be ordered due to the lack of funding. Given these setbacks, the team made its best effort to assemble the printer with the remaining time and budget but were unsuccessful in constructing a completed functioning printer.

5.2. Hardware/ Physical Components
Regarding the physical construction of the printer, all the major components were created and assembled, but without sufficient time to fully integrate them and test them working as a system.

The printer’s Z-axis motion system utilizing linear rails and a leadscrew works extremely well despite the anti-backlash nut still being absent and substituted with a standard leadscrew nut. The bed remains precisely located and motion is very repeatable based on initial testing, but without being able to perform longer term testing under printing conditions no conclusive evaluation can be made of the effectiveness of this implementation.

The V-slot axes are all acting as proof of concept and are not fit for any type of long-term use as they stand. Actual V-slot extrusions could not be sourced in time for construction, and so T-slot extrusions were installed in their place to allow proof-of-concept checking. This is not a functional substitute for actual V-slot motion but worked remarkably well as a proof of concept to allow the belts to be tensioned and axes to be roughly held in place and moved. This mis-matched interface between roller and rail hindered the performance of the screw-actuated belt tensioners, but the tensioners worked well, nonetheless.

The frame was relatively straightforward to assemble and, as expected, the blind joints kept it square across its length as checked with an aluminum tooling plate. All the printed components designed to affix directly to the frame interfaced with the T-nuts well and aligned themselves readily to the frame. Prominent among these are the Z-axis and tilt motor mounts, linkage bars, and screen plate mounts. These components are responsible for tying the print stack, composed of the masking display, resin vat, FEP, Fresnel lens, and screen carrier, into the rigidity of the frame and ensuring the motors are mounted with minimal flex to maximize positional accuracy of the motion systems.
The tilt mechanism is also very difficult to test without being able to actually run a print, but the linkage calculation proved correct, and the neutral point of the linkage sets the bed level to the built plate as intended. The clearances on the bearings and interface with the motor shaft fit well, and the linkage moves smoothly throughout its range of motion. The cheap hinge installed seems to be adequate for printer use but cannot be decisively recommended without further testing.

The fan-based wash station stirrers work well when run at less than full speed, and thus the wash stirring can be controlled seamlessly by the Octopus. The combination of small rare earth magnets and standard wash bars works very well, and the setup consistently achieves constant stirring. This enables PWM speed control of the wash stirring, and even at less than half speed a visible vortex forms in the wash container and a drop of dye shows more than sufficient flowrate for keeping fresh solvent on the part through the wash cycle.

5.3. Electronics

5.3.1. Power Supplied to Components

Our power supply units were successful during testing of each individual component. We opted to enclose both power supply units in an FDM 3D printed enclosure, while using terminal blocks to create clean output wiring with each different output voltage separate.

As mentioned in Section 5.1, we were unsuccessful in building a complete working printer, and as such not every electronic component was being powered by our power supplies at the same time. Both our electromagnets and display screen were unable to be tested, as our electromagnets were not successfully wired due to time constraints with building the printer, and our LCD display panel delivery date was delayed multiple times and has still not arrived.
We tested both power supply units using a DMM to ensure they output their specified voltages, and then connected our components to make sure that each of them could be powered individually by our power supply. We found that all our electronic components were successfully powered by the two power supply units, which bodes well for our printer if it reaches a functioning testable prototype in the future.

Going forward as this project & printer are improved, it would likely be more cost and time efficient to use one PSU with a higher power rating to power all the components, while using boost & buck converters to ensure the input voltage levels for each component meet its specifications.

5.4. Software

5.4.1. Context

The software was impacted by the overall project setbacks considerably. Without parts to test, we were able to research which software options appeared viable without knowing how they worked in practice. Once the parts had arrived, some changes were made to the intended methodology in the interest of time.

5.4.2. Firmware

In the interest of time, we opted to use Marlin instead of Klipper as the control board firmware. We decided that it would be quicker and easier to use Marlin because we had previous experience installing and configuring it, unlike with Klipper which we had never used before. Marlin operates very similarly to Klipper, though it is lacking regarding kinematic proficiency. Both firmware options handle very similar G-code. By using Marlin, we were able to confirm that the control board was functioning and viable. We were able to connect the stepper driver
motors to the board and control them via G-code successfully. Klipper remains a viable option and is still recommended even though we were not able to personally test it. It is widely used and regarded firmware.

5.4.3. Web Interface

We encountered several setbacks when attempting to use various web interfaces. First, we attempted to use the intended software (Photonic3D) which proved to be the most successful. Photonic3D was installed on the Raspberry Pi successfully and the web server functioned properly, allowing us to connect to it from a separate PC. We encountered difficulties in setting up our custom printer configuration as the automatic detection software was not working properly. With more time, we believe this problem could be diagnosed and resolved and Photonic3D remains a viable option. When Photonic3D did not work we attempted to use several other options, including Prusa SL1 Firmware, Monkeyprint, and NanoDLP. We were not able to compile the Prusa firmware due to its intensive BitBake compilation process which failed many times for us. Ultimately, we decided it was not worth the time invested due to the already limited time available from the previously mentioned setbacks. Monkeyprint couldn’t function due to outdated dependencies. With NanoDLP we encountered several difficulties with installation that resulted in a lack of output of any kind from the Raspberry Pi. We again opted to move on for the sake of time. We finally decided to write a custom script to serve as a functional prototype.

Since we used a custom script, we had to find a slicer to use since we could no longer rely on the built-in slicer of Photonic3D. Many slicers use proprietary file types which obfuscate the G-code into unreadable text, such as with PrusaSlicer. We found that Z-Suite slicer from Zortrax suited our needs well as a well-known and capable slicer [36]. The most important aspect of Z-Suite, though, for our needs is the ability to export the sliced model as a ZIP file containing
the PNG mask image files and the G-code as a human-readable text file. Using this, we were able to write a Python script which parses the G-code text file for relevant commands. The G-code commands are then sent to the control board using Pyserial so the firmware can interpret them and move the motors. When the command for displaying an image occurs, we use Tkinter to display the mask on the masking screen for the appropriate amount of time. We did not reach the point of networking the script to allow it to serve as a web-interface with a GUI, thus prints must be uploaded and started manually for now.

5.4.4. API

Marlin does not require a Pi-side API unlike Klipper due to its different configuration. Klipper is designed as a bridge between the control board and Raspberry Pi and thus requires components on both ends. Marlin runs solely on the control board, so we did not use any API. We believe the Klipper API Moonraker is still a viable solution in conjunction with Klipper.

5.4.5. Touchscreen GUI

The touchscreen was one of the parts we ordered which did not arrive. Marlin has built in touchscreen capabilities though, so we were able to connect a different touchscreen unrelated to the project to test the functionality. The touchscreen worked successfully, though that was the extent of our testing, because the printer was not functional otherwise.

5.5. Chemicals

The result of our resin cure tests was somewhat successful and unsuccessful. When attempting to cure the resin within the Original Anycubic Photon printer, the resin had a difficult time polymerizing. The product of these prints was an uncured vat of resin thus unsuccessful. However, we then took this resin and exposed it throughout the day to sunlight, in hopes that this
long-term exposure would have some effect on the resin. This resulted in full polymerization and curing of the resin. This result leads us to believe that the photoinitiator of the resin was struggling to activate and form free radical electrons fast enough to be reasonable for 3D printing purposes. Due to this we recommend for future tests of this resin composition, another photoinitiator additive should be included to further facilitate the proliferation of free radical electrons in the resin solution. One possible photoinitiator additive could be Lithium phenyl (2,4,6-trimethylbenzoyl) phosphinate (LAP). This molecule, as shown in the figure below, also undergoes free radical formation in the presence of ultraviolet light and thus could increase the concentration of available radicals for polymerization [16].

![Mechanism of Radical Generation](image)

*Figure 11: LAP Radical Generation*

This figure shows the process by which the molecule Lithium phenyl (2,4,6-trimethylbenzoyl) phosphinate can generate two free radical electrons when exposed to ultraviolet light [37].

Further work for resin creation on this project would utilize the research conducted on resin biocompatibility and bacterial resistance. As mentioned previously in this paper, additives such as silver and other metal ion nanoparticles could be added to resins to increase the resistance of bacterial growth on the cured resin products. The use of this added bacterial resistance has implications for dental resins as well as other biomedical implants that resins can
be created into. To test the effectiveness of bacterial resistance additives, an ELISA assay could be run on a cured resin product. By plating the resin and attempting to grow bacteria we could observe possible zones of inhibition and therefore determine the bacterial growth inhibition properties of certain resin additives.
References


Appendix A – Assembly Instructions

1. Extrusion Preparation
   a. Hole drilling: Extrusion
   b. Identification and exact hole locations are listed in Figure 15, hole positions on extrusions in Figures 11 and 12 as numbered in Appendix D.
   c. End tapping: Existing holes in ends of extrusions are tapped ~5-10mm deep with an M5 tap to facilitate blind joints as specified in Figure 14

2. Printed Parts
   a. Print all required parts according to CAD assembly
   b. Fit heat set inserts as needed according to CAD assembly
   c. Slid bed halves together around electromagnet, feed wire through channel, and glue halves together (4x)

3. Acrylic Parts
   a. All acrylic parts are laser cut from .25” or .125” sheet acrylic
   b. Holes are fitted with heat set inserts as shown in CAD assembly
   c. If clear acrylic is used, wrap lower panels with black adhesive vinyl and upper panels with UV blocking film. Trim all excess and poke out holes

4. Frame Construction
   a. 4040 extrusions that make up printer frame are assembled, but not fully tightened, first according to layout show in Figure 13
   b. 2040 and 2020 extrusions that make up wash and cure frame are assembled loosely following Figure 13, then slid onto the printer frame
   c. Entire frame is placed on a flat surface to keep square, then printer frame B extrusions are slid out so that wash and cure can be tightened onto them
   d. Wash and cure tightened onto printer frame rails, then entirely tightened
   e. Printer B rails are slid back into place, then printer frame is tightened

5. Motion Axes
   a. Z-axis linear rails are affixed with an M3 BHCS and T-nut in every other hole
   b. V-slot wheel carrier plates are assembled with rollers and tensioner sliders
   c. Wash and cure motor mounts are assembled with motors, pulleys, and idlers, then installed on undersides of acrylic top plates
   d. Wash and cure idlers are assembled with idler pulleys and mounted to frame
   e. Z-axis motor mount is attached to frame and motor is attached
   f. Top plate is installed with printed brackets over the motor before coupler and lead screw are affixed to motor shaft, sandwiching the top plate
   g. Tilt motor mount is attached to frame and motor installed, then bearings are pressed into tilt linkages and the assembly is slid onto the motor shaft
   h. The tilt linkage is left hanging out of the way near the top plate
   i. The overhead motor mount is assembled with motor and pulley, then mounted to overhead rail
      i. Note: this will have to be removed to install the side plate, so it is only installed now for testing
6. Belt Routing
   a. Wash/cure belts
      i. Start belt in maze on wheel plate
      ii. Feed belt up and over idler
      iii. Feed belt down through slit in top plate
      iv. Loop belt around motor pulley and idler
      v. Feed belt back up through second slit in top plate
      vi. Secure belt in second maze on wheel plate
      vii. Assemble tensioner slider with idler and slip into place
      viii. Tension
   b. Overhead belt
      i. Start belt in maze on wheel plate
      ii. Feed belt across and around idler
      iii. Feed belt back across by tensioner idlers
         1. During final assembly, through slit in side plate
      iv. Loop belt around motor pulley
         1. During final assembly, through other slit in side plate
      v. Secure belt in second maze on wheel plate
      vi. Assemble tensioner slider with idler and slip into place
      vii. Tension

7. Bed Carrier Assembly and Mounting
   a. Printer:
      i. Leadscrew nut is screwed into leadscrew block with M2 screws
      ii. Leadscrew block is affixed to bed carrier arm with M5 screws
      iii. Bed arm is affixed to bed carrier with using M5 screws
      iv. Bed plate is affixed to bed carrier using M5 screws
      v. Bed arm is affixed to bearing blocks of linear rails using M3 screws
   b. Wash and Cure:
      i. Bed arm extrusions are blind jointed together
      ii. Shorter extrusion is installed into bed carrier plate using T-nuts
      iii. Longer extrusion is installed into wheel carrier plate using T-nuts
      iv. Bed plate is affixed to bed carrier using M5 screws

8. Top Plate and Screen Carrier Assembly
   a. Screen carrier must be completely clean and free of dust/debris before proceeding
   b. Outer edges of screen carrier (anywhere outside of display area) are wrapped with black vinyl
   c. Hinge is mounted to screen carrier using M3 screws
   d. Masking display is placed on bottom of screen carrier with front of display against the acrylic
   e. Fresnel lens is placed on top of screen according to manufacturer orientation specifications
   f. Screen hold-down clips are screwed in place over display-lens stack using M3 hardware
g. Screen carrier is placed into printer and other side of hinge is affixed to top panel using M3 screws
h. Tilt linkage screen link is affixed to screen carrier using M3 screws

9. Build Vat Assembly
   a. End faces of shorter extrusions are coated with room temperature vulcanizing (RTV) silicone sealant
   b. Extrusions are blind jointed together into a rectangle with care taken to ensure silicone remains neat and seals effectively
c. Printed vat ring is glued together if printed in multiple parts, and an O ring is made to match the length required for the included boss
d. Vat ring is fixed to bottom of vat extrusions using M3 hardware and T nuts in a few locations
e. FEP sheet is cut roughly to size, sandwiched between two bed rings, holes for screws are made, and screws are fed through
f. FEP and bed-ring stack is placed on printed side of vat loaded with T-nuts
g. Screws are tightened evenly in a star-equivalent pattern to tighten the stack
   i. Vat ring is pulled against extrusions and O ring seals against extrusion face
   ii. Bed rings are pulled into boss in vat ring, tensioning FEP
h. Final check to ensure no screws sit proud of bottom face of bed- will scratch acrylics screen carrier

10. Electronics Mounting
    a. Cure light is affixed to frame using included bracket and T-nuts
    b. Wash fans are mounted to underside of wash acrylic tops using long M3 screws
c. Pigtail is wired to 12V PSU input, and mains power enclosure is mounted to PSU
d. Terminal bars and 24V PSU are installed in mains power enclosure
e. Wiring lead for power socket and extra ground strap are wired to terminal bars and fed through to outside of enclosure
f. Mains power enclosure and PSUs are placed on printer bottom panel and affixed with double-sided tape
g. Ground strap is affixed to frame using T-nut
h. Printed mounts are screwed into electronics panel and used to mount to frame about mains enclosure
   i. Octopus, Pi, LED driver, relays, boost converters, and display driver are mounted to electronics panel using screws

11. Software
    a. Follow online instructions for installing Marlin (or Klipper) firmware and install it to the Octopus control board
    b. Install your preferred OS (i.e. Raspbian OS) on the Raspberry Pi by following online instructions. Python should be installed by default, if it is not make sure to install python.
c. Follow instructions in Appendix C for setting up the software on the Raspberry Pi.
d. Install Zortrax Z-Suite to your preferred computer for slicing 3D models.
e. In Zortrax export slice as a ZIP and extract the contents of the zip to match the file structure in Appendix C.
# Appendix B – Complete Components List

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Model/Part # (w/ Link)</th>
<th>Part Quantity</th>
<th>Part Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl Methacrylate Polymer (500 g)</td>
<td>M0088</td>
<td>1</td>
<td>$70.00</td>
<td>$70.00</td>
</tr>
<tr>
<td>Diphenyl(2,4,6-trimethylbenzoyl)phosphine Oxide (25 g)</td>
<td>D3358</td>
<td>1</td>
<td>71.00</td>
<td>71.00</td>
</tr>
<tr>
<td>Butyl Methacrylate (stabilized with HQ) (500 mL)</td>
<td>M0081</td>
<td>1</td>
<td>24.00</td>
<td>24.00</td>
</tr>
<tr>
<td>Bis(2-butoxyethyl) Adipate (25 g)</td>
<td>B2716</td>
<td>2</td>
<td>29.00</td>
<td>58.00</td>
</tr>
<tr>
<td>M3x30 SHCS</td>
<td>91292A022</td>
<td>1</td>
<td>$5.18</td>
<td>$5.18</td>
</tr>
<tr>
<td>M3x12 SHCS</td>
<td>91292A114</td>
<td>1</td>
<td>$6.00</td>
<td>$6.00</td>
</tr>
<tr>
<td>M3x8 BHCS</td>
<td>92095A181</td>
<td>1</td>
<td>$8.90</td>
<td>$8.90</td>
</tr>
<tr>
<td>M3x5 BHCS</td>
<td>94500A263</td>
<td>1</td>
<td>$3.54</td>
<td>$3.54</td>
</tr>
<tr>
<td>M5x18 SHCS</td>
<td>91292A127</td>
<td>1</td>
<td>$10.60</td>
<td>$10.60</td>
</tr>
<tr>
<td>M5x16 SHCS</td>
<td>91274A129</td>
<td>1</td>
<td>$5.61</td>
<td>$5.61</td>
</tr>
<tr>
<td>M5x8 SHCS</td>
<td>91274A125</td>
<td>1</td>
<td>$6.70</td>
<td>$6.70</td>
</tr>
<tr>
<td>M5x25 BHCS</td>
<td>92095A216</td>
<td>1</td>
<td>$7.64</td>
<td>$7.64</td>
</tr>
<tr>
<td>M5x10 BHCS</td>
<td>94500A297</td>
<td>1</td>
<td>$10.17</td>
<td>$10.17</td>
</tr>
<tr>
<td>M5x25 FBHCS</td>
<td>90909A154</td>
<td>1</td>
<td>$10.96</td>
<td>$10.96</td>
</tr>
<tr>
<td>M5x8 FBHCS</td>
<td>90909A721</td>
<td>1</td>
<td>$13.92</td>
<td>$13.92</td>
</tr>
<tr>
<td>M5x6 FBHCS</td>
<td>97654A678</td>
<td>1</td>
<td>$7.40</td>
<td>$7.40</td>
</tr>
<tr>
<td>4040 T Slot Extrusion</td>
<td>HF55-4040-790</td>
<td>4</td>
<td>$14.61</td>
<td>$58.44</td>
</tr>
<tr>
<td>4040 T Slot Extrusion</td>
<td>HF55-4040-710</td>
<td>1</td>
<td>$13.13</td>
<td>$13.13</td>
</tr>
<tr>
<td>4040 T Slot Extrusion</td>
<td>HF55-4040-300</td>
<td>4</td>
<td>$5.55</td>
<td>$22.20</td>
</tr>
<tr>
<td>4040 T Slot Extrusion</td>
<td>HF55-4040-250</td>
<td>4</td>
<td>$5.03</td>
<td>$20.12</td>
</tr>
<tr>
<td>Smooth Sided 2040 T Slot Extrusion</td>
<td>HF55-2040-281.5</td>
<td>2</td>
<td>$3.66</td>
<td>$7.32</td>
</tr>
<tr>
<td>Smooth Sided 2040 T Slot Extrusion</td>
<td>HF55-2040-139.5</td>
<td>2</td>
<td>$3.66</td>
<td>$7.32</td>
</tr>
<tr>
<td>2040 T Slot Extrusion</td>
<td>HF5-5-2040-1614</td>
<td>1</td>
<td>$20.98</td>
<td>$20.98</td>
</tr>
<tr>
<td>2040 T Slot Extrusion</td>
<td>HF5-5-2040-670</td>
<td>3</td>
<td>$8.71</td>
<td>$26.13</td>
</tr>
<tr>
<td>2040 T Slot Extrusion</td>
<td>HF5-5-2040-290</td>
<td>1</td>
<td>$3.12</td>
<td>$3.12</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-1010</td>
<td>6</td>
<td>$6.96</td>
<td>$41.76</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-750</td>
<td>4</td>
<td>$5.17</td>
<td>$20.68</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-290</td>
<td>6</td>
<td>$3.31</td>
<td>$19.86</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-280</td>
<td>2</td>
<td>$3.31</td>
<td>$6.62</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-247.5</td>
<td>1</td>
<td>$3.31</td>
<td>$3.31</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-142</td>
<td>3</td>
<td>$3.31</td>
<td>$9.93</td>
</tr>
<tr>
<td>2020 T Slot Extrusion</td>
<td>HF55-2020-60</td>
<td>3</td>
<td>$3.31</td>
<td>$9.93</td>
</tr>
<tr>
<td>Raspberry Pi 4 Model B Starter Kit, Essential Parts</td>
<td>N/A</td>
<td>1</td>
<td>58.54</td>
<td>58.54</td>
</tr>
<tr>
<td>Description</td>
<td>Model Number</td>
<td>Quantity</td>
<td>Unit Price 1</td>
<td>Unit Price 2</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>-------------------------</td>
<td>----------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>LCD TFT 7&quot; 800480 24BIT RGB RTP</td>
<td>2544-AFK800480A0-7.0N12NTM-R-ND</td>
<td>1</td>
<td>$36.04</td>
<td>$36.04</td>
</tr>
<tr>
<td>5K 10.1&quot; Monochrome LCD Display</td>
<td>RV101FBB-N00</td>
<td>1</td>
<td>$250.00</td>
<td>$250.00</td>
</tr>
<tr>
<td>405nm Parallel UV LED Module</td>
<td>UVA-S64</td>
<td>1</td>
<td>$130.00</td>
<td>$130.00</td>
</tr>
<tr>
<td>BTT Octopus V1.1</td>
<td>1877685</td>
<td>1</td>
<td>$46.99</td>
<td>$46.99</td>
</tr>
<tr>
<td>IEC320 C14 to C13 Extension Cord</td>
<td>N/A</td>
<td>1</td>
<td>$2.62</td>
<td>$2.62</td>
</tr>
<tr>
<td>4x1&quot; Magnetic Stirrer Bars</td>
<td>N/A</td>
<td>1</td>
<td>$6.39</td>
<td>$6.39</td>
</tr>
<tr>
<td>3D Printer V Slot Wheels</td>
<td>N/A</td>
<td>1</td>
<td>$13.99</td>
<td>$13.99</td>
</tr>
<tr>
<td>5mm Bore 10mm W 16 TGT2 Idler</td>
<td>N/A</td>
<td>1</td>
<td>$12.58</td>
<td>$62.90</td>
</tr>
<tr>
<td>9mm W GT2 Belt w/ Pulleys</td>
<td>N/A</td>
<td>1</td>
<td>$25.88</td>
<td>$25.88</td>
</tr>
<tr>
<td>M5x6x7 Heat Set Inserts</td>
<td>N/A</td>
<td>1</td>
<td>$9.49</td>
<td>$9.49</td>
</tr>
<tr>
<td>M3x5x5mm Heat Set Inserts</td>
<td>N/A</td>
<td>1</td>
<td>$9.99</td>
<td>$9.99</td>
</tr>
<tr>
<td>M5 T Nuts</td>
<td>N/A</td>
<td>1</td>
<td>$9.59</td>
<td>$9.59</td>
</tr>
<tr>
<td>M3 T Nuts</td>
<td>N/A</td>
<td>1</td>
<td>$6.99</td>
<td>$6.99</td>
</tr>
<tr>
<td>T8x8 Leadscrew</td>
<td>N/A</td>
<td>1</td>
<td>$6.99</td>
<td>$6.99</td>
</tr>
<tr>
<td>MGN9H Linear Rails</td>
<td>N/A</td>
<td>1</td>
<td>$37.99</td>
<td>$37.99</td>
</tr>
<tr>
<td>5x2mm Neodymium Magnets</td>
<td>N/A</td>
<td>1</td>
<td>$5.99</td>
<td>$5.99</td>
</tr>
<tr>
<td>12V 200N Electromagnet</td>
<td>N/A</td>
<td>4</td>
<td>$15.49</td>
<td>$61.56</td>
</tr>
<tr>
<td>5-Pack 120mm Cooling Fan</td>
<td>N/A</td>
<td>1</td>
<td>$21.44</td>
<td>$21.44</td>
</tr>
<tr>
<td>24V 5A 120W External PSU</td>
<td>N/A</td>
<td>1</td>
<td>$20.99</td>
<td>$20.99</td>
</tr>
<tr>
<td>3-Pack NEMA-17 Stepper Motor</td>
<td>N/A</td>
<td>2</td>
<td>$23.99</td>
<td>$23.99</td>
</tr>
<tr>
<td>PLA Filament (Blue)</td>
<td>N/A</td>
<td>1</td>
<td>$19.99</td>
<td>$19.99</td>
</tr>
<tr>
<td>PLA Filament (Red)</td>
<td>N/A</td>
<td>1</td>
<td>$19.99</td>
<td>$19.99</td>
</tr>
<tr>
<td>PLA Filament (Yellow)</td>
<td>N/A</td>
<td>1</td>
<td>$19.99</td>
<td>$19.99</td>
</tr>
<tr>
<td>5-Pack 16GB Mico SD Card</td>
<td>N/A</td>
<td>1</td>
<td>$17.50</td>
<td>$17.50</td>
</tr>
<tr>
<td>2-Pack 8.5-50V to 10-60V Step Up Boost Converter</td>
<td>N/A</td>
<td>1</td>
<td>$14.59</td>
<td>$14.59</td>
</tr>
<tr>
<td>0.15mm Thick FEP Film Sheets</td>
<td>N/A</td>
<td>1</td>
<td>$7.99</td>
<td>$7.99</td>
</tr>
<tr>
<td>192x126mm Magnetic Steel Print Bed Build Plate</td>
<td>N/A</td>
<td>1</td>
<td>$20.18</td>
<td>$20.18</td>
</tr>
<tr>
<td>Mean Well 12V 17A 200W PSU</td>
<td>N/A</td>
<td>1</td>
<td>$26.95</td>
<td>$26.95</td>
</tr>
<tr>
<td>2.1x5.5mm 12V Jack Plug Power Adapter Connector</td>
<td>N/A</td>
<td>1</td>
<td>$4.99</td>
<td>$4.99</td>
</tr>
<tr>
<td>Continuous Pin 24x1-1/4&quot; Nickel Hinge</td>
<td>N/A</td>
<td>1</td>
<td>$8.99</td>
<td>$8.99</td>
</tr>
<tr>
<td>12V to 5V 3A 15W DC Buck Converter Module</td>
<td>N/A</td>
<td>1</td>
<td>$9.49</td>
<td>$9.49</td>
</tr>
<tr>
<td>0.8x50mm Socket Head Cap Screws</td>
<td>N/A</td>
<td>1</td>
<td>$8.99</td>
<td>$8.99</td>
</tr>
<tr>
<td>3.5mm Nickel Stereo Plug</td>
<td>N/A</td>
<td>1</td>
<td>$5.25</td>
<td>$5.25</td>
</tr>
<tr>
<td>6x15x5mm Miniature Steel Bearings</td>
<td>N/A</td>
<td>1</td>
<td>$7.98</td>
<td>$7.98</td>
</tr>
<tr>
<td>Product Description</td>
<td>Unit</td>
<td>Quantity</td>
<td>Original Price</td>
<td>New Price</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>------</td>
<td>----------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>Anti-UV Adhesive Vinyl Sheets</td>
<td>N/A</td>
<td>1</td>
<td>$22.99</td>
<td>$22.99</td>
</tr>
<tr>
<td>Wire Terminal Crimper Tool &amp; Wire Terminal Connectors</td>
<td>N/A</td>
<td>1</td>
<td>$25.99</td>
<td>$25.99</td>
</tr>
<tr>
<td>UV Resin Solar Display Stand Turntable</td>
<td>N/A</td>
<td>1</td>
<td>$7.99</td>
<td>$7.99</td>
</tr>
<tr>
<td>405nm 6W UV Resin Curing Light</td>
<td>N/A</td>
<td>1</td>
<td>$19.99</td>
<td>$19.99</td>
</tr>
<tr>
<td>10A Fuse Switch Male Power Socket</td>
<td>N/A</td>
<td>1</td>
<td>$8.99</td>
<td>$8.99</td>
</tr>
<tr>
<td>8mm Button Head Socket Cap Screws</td>
<td>N/A</td>
<td>1</td>
<td>$6.59</td>
<td>$6.59</td>
</tr>
<tr>
<td>Matte Black Vinyl Sheets</td>
<td>N/A</td>
<td>1</td>
<td>$16.25</td>
<td>$16.25</td>
</tr>
</tbody>
</table>
Appendix C – Custom Firmware Code

(On next page)

The folder structure is as follows:

Top Level Folder

➔ AutoMSLA.py (Main Firmware file)
➔ Print_Files (Folder containing contents of Z-Suite ZIP file)
   ○ Images (Folder containing PNGs of mask images)
      ▪ 1.png
      ▪ 2.png
      ▪ ...
      ▪ N.png
   ○ gcode.txt (Change filename of run.gcode to gcode.txt)
import serial
import time
import tkinter
from PIL import Image, ImageTk
from operator import contains

ser = serial.Serial('/dev/ttyAMA0', 250000)
time.sleep(2)

def sendCommand(ser, command):
    ser.write(str.encode(command))
time.sleep(1)

while True:
    line = ser.readline()
    print(line)

    if line == b'ok
':
        break

with open('Print_Files/gcode.txt') as f:
    for line in f:
        if not(line[:1] == ';' or line.isspace()):
            if contains(line, "show Image"):
                result = line.split('"')[1::2]
                imgName = result[0]
                pilImage = Image.open("Print_Files/Images/" + imgName)
                fit_center(pilImage, rootpkg)
Appendix D – Assembly References

Figure 12: List of hole locations for all extrusions, 1 of 2 (note: subject to change with further work on prototype)
Figure 13: List of hole locations for all extrusions, 2 of 2 (note: subject to change with further work on prototype)
Figure 14: Locations of Extrusions on Completed Frame Assembly
<table>
<thead>
<tr>
<th>Printer Only</th>
<th>Type</th>
<th>ID</th>
<th>Qty.</th>
<th>L [mm]</th>
<th>Description</th>
<th>Tapped Ends</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4040</td>
<td>A</td>
<td>2</td>
<td>790</td>
<td>printer uprights</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4040</td>
<td>B</td>
<td>2</td>
<td>790</td>
<td>printer uprights +WC</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4040</td>
<td>C</td>
<td>4</td>
<td>250</td>
<td>printer spreaders</td>
<td>2x 2e/ diag.</td>
</tr>
<tr>
<td></td>
<td>4040</td>
<td>D</td>
<td>2</td>
<td>300</td>
<td>printer horz.</td>
<td>2x 2e/ diag.</td>
</tr>
<tr>
<td></td>
<td>4040</td>
<td>E</td>
<td>2</td>
<td>300</td>
<td>printer horz. +Z</td>
<td>2x 2e/ diag.</td>
</tr>
<tr>
<td></td>
<td>4040</td>
<td>F</td>
<td>1</td>
<td>710</td>
<td>Z</td>
<td>2x 2e/ diag.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1x 20mm longer for cure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2040</td>
<td>G</td>
<td>3</td>
<td>670</td>
<td>WC axes</td>
<td>2x 2e/</td>
</tr>
<tr>
<td></td>
<td>2040</td>
<td>H</td>
<td>1</td>
<td>290</td>
<td>cure spreader</td>
<td>2x 2e/</td>
</tr>
<tr>
<td></td>
<td>2040</td>
<td>I</td>
<td>1</td>
<td>1614</td>
<td>overhead rail</td>
<td>1x 2e/</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>J</td>
<td>6</td>
<td>290</td>
<td>WC spreaders</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>K</td>
<td>2</td>
<td>1010</td>
<td>WC full horz. lower</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>L</td>
<td>1</td>
<td>1010</td>
<td>WC full horz. upper</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>M</td>
<td>1</td>
<td>1010</td>
<td>WC full horz. upper +axes</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>N</td>
<td>1</td>
<td>690</td>
<td>wash horz.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>O</td>
<td>1</td>
<td>690</td>
<td>wash horz. +axes</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>P</td>
<td>1</td>
<td>280</td>
<td>cure horz.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>Q</td>
<td>1</td>
<td>280</td>
<td>cure horz. +axis</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>R</td>
<td>2</td>
<td>670</td>
<td>wash vert.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>S</td>
<td>2</td>
<td>750</td>
<td>cure vert.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>T</td>
<td>2</td>
<td>750</td>
<td>cure vert. +spreader</td>
<td>2</td>
</tr>
</tbody>
</table>

*Figure 15: Extrusion length and tapping specifications*
### Hole Locations [mm]

<table>
<thead>
<tr>
<th>ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>30</td>
<td>-30</td>
<td>-10</td>
<td>10</td>
<td>30</td>
<td>-30</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>90</td>
<td>-30</td>
<td>-10</td>
<td>10</td>
<td>30</td>
<td>-30</td>
<td>-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>140</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>10</td>
<td>30</td>
<td>350</td>
<td>370</td>
<td>730</td>
<td>730</td>
<td>-534</td>
<td>-534</td>
<td>-234</td>
<td>-234</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>-310</td>
<td>-10</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>350</td>
<td>-310</td>
<td>-10</td>
<td>350</td>
<td>-310</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>165</td>
<td>185</td>
<td>350</td>
<td>515</td>
<td>535</td>
<td>-310</td>
<td>-170</td>
<td>-150</td>
<td>-10</td>
<td>350</td>
<td>-310</td>
<td>-10</td>
</tr>
<tr>
<td>N</td>
<td>10</td>
<td>350</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>10</td>
<td>165</td>
<td>185</td>
<td>350</td>
<td>-175</td>
<td>-155</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>130</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>50</td>
<td>70</td>
<td>50</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: Holes are located at specified distance from left end of extrusion as shown in Figures 11 and 12 unless negative, when location is specified as distance from right end. Consult figures 11 and 12 to determine which side/rail of the extrusion each hole should fall on. If an extrusion is not listed, assume there are no holes on that piece.*
Appendix E - Incomplete Hardware Aspects of Prototype (Future Work)

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated time to implement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement printer bed leveling adjustment mechanism</td>
<td>3 hours</td>
</tr>
<tr>
<td>Overhead rail belt routing and tensioning</td>
<td>0.5 hour</td>
</tr>
<tr>
<td>Cure station turntable implementation</td>
<td>1 hour</td>
</tr>
<tr>
<td>Completion of acrylic enclosure cutting/installation</td>
<td>2 hours</td>
</tr>
<tr>
<td>Construction of final resin vat (extrusions backordered)</td>
<td>2 hours</td>
</tr>
<tr>
<td>Wiring relays to Pi GPIO</td>
<td>3 hours</td>
</tr>
<tr>
<td>Wiring electromagnets to relays</td>
<td>1 hour</td>
</tr>
<tr>
<td>Wiring overhead motor</td>
<td>0.25 hour</td>
</tr>
<tr>
<td>Troubleshoot intermittent issue with LED driver</td>
<td>Unknown</td>
</tr>
</tbody>
</table>