PROTOTYPE DATA

DLP 3D PRINTER USING LC4500-UV PROJECTOR

PREPARED BY:

CALEB FROME, ELISE HOLLAND, ALAINA KUNZMAN

KEYNOTE PHOTONICS

SUBMITTED TO:

ADAM KUNZMAN

CEO KEYNOTE PHOTONICS

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1.1 TYPES OF 3D PRINTERS

1.1.1 The Filament-Based 3D Printer

A filament-based 3D printer creates an object by melting plastic filament and reforming it into a three-dimensional shape, layer-by-layer. An extruder liquefies the filament by heating it to 230°C. At this high temperature, the filament will not stick to the extruder and can be easily manipulated into any shape. At the bottom of the print bed is the build plate, heated to 80°C to ensure that the filament adheres to it. The extruder moves in the x-y plane, applying the melted filament to the top level of the build. The first layer is applied directly to the build plate; each subsequent layer is drawn on top of its predecessor. As the filament leaves the extruder and comes into contact with the air, it cools almost instantaneously, curing in a matter of microseconds. After each layer is complete, the build plate and the attached build move downwards to prepare for the next layer.

1.1.2 The SLA 3D Printer

An SLA 3D printer operates under the same basic premise as filament-based printers: a three-dimensional object is created by curing a source material layer-by-layer, using a baseplate as the build platform. The key difference is the source material and the curing mechanism. An SLA 3D printer uses liquid resin rather than plastic filament as the build material, and the curing agent is not heat but UV light. The resin is stored in a vat which also contains the build plate, submerged in the resin. A UV DLP displays patterns specific to the various layers, curing the resin into precise shapes. After each layer has been cured, the build plate moves away from the projector to prepare for the next layer to form. The specific orientation of the vat, projector, and build plate varies, but SLA 3D printers are typically constructed according to one of two paradigms: top-down or bottom-up. In a top-down printer, the projector is positioned above the vat and shines down onto the baseplate, which starts at the top of the vat and moves downward into the resin. The printed object is submerged in the resin at all times. By contrast, in a bottom-up printer, the projector is positioned below the vat and shines through it to cure against the baseplate on the other side. As the print progresses, the baseplate and attached object rise out of the vat. While the curing time for resin can take several seconds, an entire layer can cure at once, allowing an SLA 3D printer to achieve much faster print times than a filament-based printer, especially for designs with large cross-sectional areas.

1.2 SCOPE OF WORK

The prototype created in this project is a bottom-up 3D SLA printer with one key design modification. Whereas in a traditional bottom-up design the baseplate moves up as each layer is printed, in this design, the vat and projector move downward from the build plate, which remains in a constant position. The DLP is positioned on its side; a mirror set at a 45° angle reflects the projected patterns upward toward the vat. The projector and the vat are attached to the same structure to ensure the distance between them remains constant, and that they move in unison.

The main purpose of this prototype was to demonstrate a working 3D SLA printer using the LC4500-UV as the DLP, and to verify the effectiveness of the stationary baseplate design. It is intended to provide a starting point from which an X-axis may be added, enabling the projector to scroll back and forth, increasing the maximum baseplate size so that larger objects may be printed.

2 BACKGROUND AND PREVIOUS WORK

2.1 CONSTRUCTION

The decision to build a bottom-up prototype was based on research into two existing DLP 3D printers: a bottom-up design from the University of Twente and a top-down design from Texas Instruments. In summary, top-down printers are relatively simple to build, but are not cost-effective in terms of the amount of resin used. On the other hand, bottom-up printers are much more mechanically complex, but are able to vastly reduce the amount of resin used. For this project, the cost was the highest priority, so the bottom-up design was chosen.

2.1.1 Top-Down Design

In a top-down printer, the projector is positioned above the vat and shines down onto the baseplate, which starts at the top of the vat and moves downward into the resin. When a layer is created, only the resin at the topmost layer of the vat is cured [1]. The first layer cures to the top of the baseplate; each subsequent layer cures to the top of the previous layer. After curing, the hardened resin remains submerged as the build plate descends into the vat. Because the final object is always submerged in the resin, the build dimensions are limited to the size of the vat, which must always be completely filled. After every print, any leftover resin must be discarded because of risk of contamination between prints. The amount of resin wasted can easily exceed the amount of resin used in the actual print, particularly for designs with layers which do not occupy the entire length and width available. Because of the high price of resin, this printer orientation can become very expensive very quickly (Texas Instruments).

2.1.2 Bottom-Up Design

In a bottom-up printer, the projector is positioned below a clear Plexiglass vat so that it cures the resin between the build plate and the bottom of the vat. The first layer cures to the underside of the baseplate, which rises out of the vat, allowing more resin to flow in underneath it. This resin is then cured to form the next layer, which adheres to the previous layer. This design offers the significant advantage of requiring only as much resin as is necessary to print the object. Any leftover resin must still be discarded, but the exact amount can be used so that very little is wasted. Thus, the cost per print is significantly less (University of Twente, 23). However, because the resin cure area is the space between the baseplate/build and the bottom of the vat, as the resin cures, it adheres to both the build and to the bottom of the vat. After each layer is created, the object must be peeled off the vat surface, which can prove a rather difficult task due to the vacuum created between the resin and the Plexiglass. A special peeling mechanism must be installed to break this seal after each layer is cured. Several such mechanisms have been designed, all of which are difficult to build due to their complexity. Peeling systems are discussed in more detail in Vat Arms and Spring System, Passive Tilt System, Vat and Spring System, and Vat and Arm Construction Information.

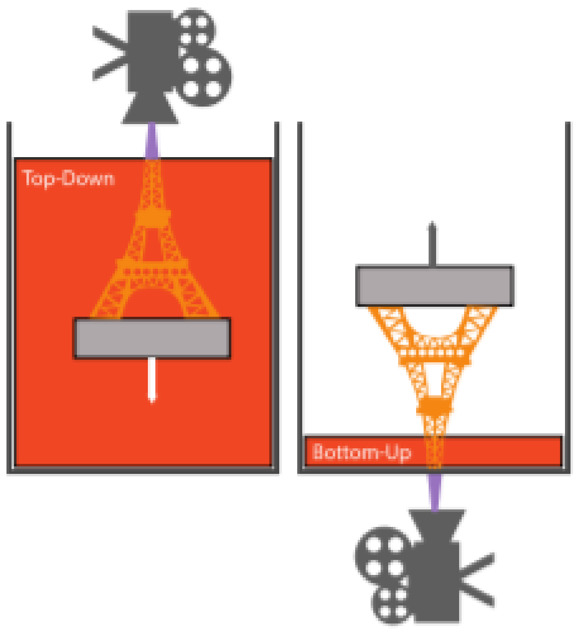

Figure 1 Top-Down Verses Bottom-Up Printer

3 EXPERIMENT THEORY

3.1 CONSTRUCTION

3.1.1 Movement

Although this prototype does not support horizontal projector movement, it was designed with the intent of adding an X-axis in a later version. A 3D printer is a precise machine; if the number of moving parts is kept at a minimum, the margin for error is reduced, and the print accuracy increases. With this in mind, it was logical to keep the baseplate constant, instead allowing the projector and vat to move. In this prototype, the only movement is along the Z-axis, but in future designs, the projector/vat system will move in the X-Z plane. While this is a deviation from typical bottom-up designs, in which the build plate and printed object move upwards out of the vat, the net effect is the same. Regardless of whether the baseplate moves away from the vat or the vat/projector assembly moves away from the baseplate, the basic layered building process does not change (Figure 2).

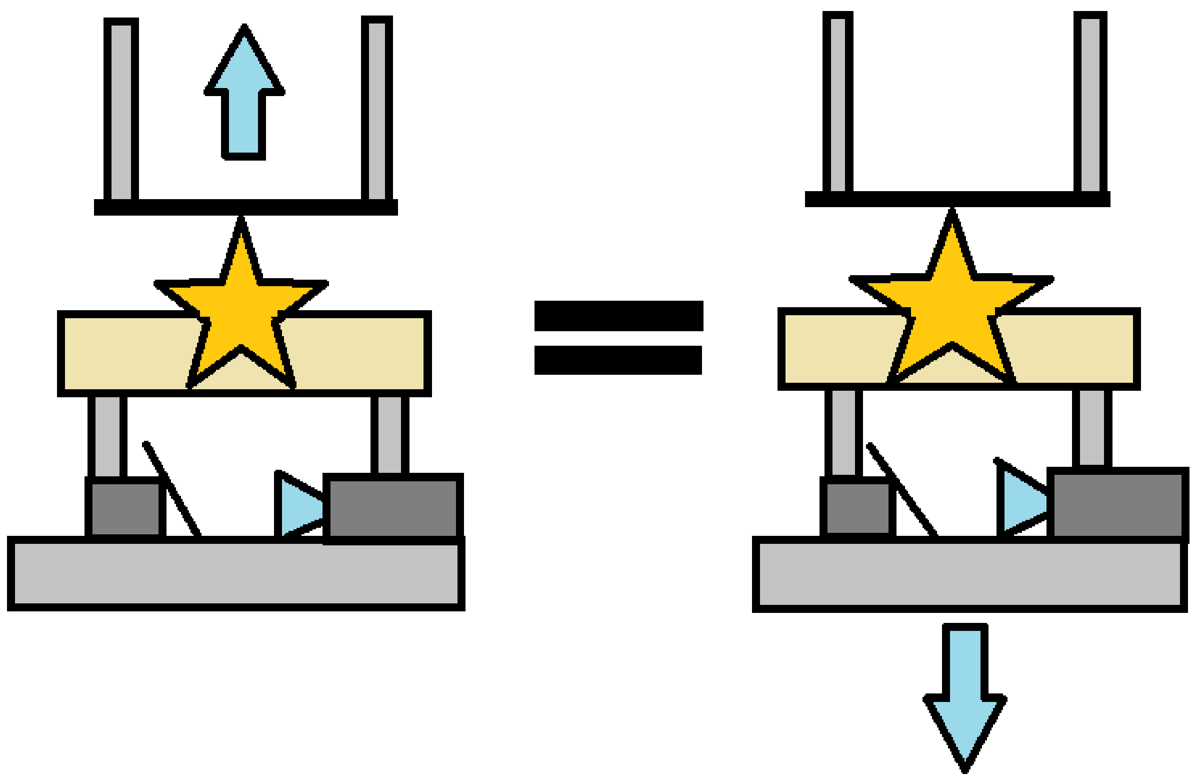

Figure 2 Force Distribution Illustration

3.1.2 Z-Axis

Z-axis movement is typically accomplished using a lead screw or threaded rod. Threaded rods are built with less precision than lead screws and are more prone to wobbling, but are cheaper to manufacture. A lead screw may be appropriate for a future, more permanent version of this prototype, but this prototype requires no more precision than the cheaper threaded rod can offer. The prototype mini uses a T8 threaded rod (300mm x 8mm) with four starts and a pitch of 2mm, creating a lead of 8mm.

The vat/projector assembly is attached to the threaded rod as a single unit which is raised and lowered by a step motor which controls the rotation of the rod. These components are attached to the threaded rod with special nuts which are designed to prevent frictional and rotational backlash by converting rotational motion to linear motion, which is more stable. Additional stability is provided by two different 5/16 inch diameter smooth steel rods which reduce the torque on the threaded rod by distributing the weight of the projector and vat more evenly. One of these rods is located on either side of the threaded rod, and the third is positioned on the opposite side of the baseplate. This can be viewed in both figures of theFigure 9 Original Prototype Design and the Figure 10 Prototype located in Figures and Information.

3.1.3 Passive Tilt System

In bottom-up printers, when each layer cures, it hardens to both the previous layer and to the bottom of the vat. A peeling mechanism is required to break the vacuum that forms between the resin and the bottom of the vat. This mechanism can be placed on the build plate or on the vat. For this prototype, the mechanism will be placed on the vat because it can be built into the already moving mechanism. The vat utilizes a passive tilt system inspired by a design from the University of Twente to peel the cured layers of the build from the bottom of the vat. In order to accomplish this, a spring is placed between the wooden slats which secure the vat handles and the wing nuts. The wing nuts are tightened to different strengths depending on the side of the vat assembly; one side is tightened more than the other. When the vat pulls away from the build plate, the passive tilt system will redistribute the applied force to the cured layer, allowing a peeling action to take place (Holtrup 44).

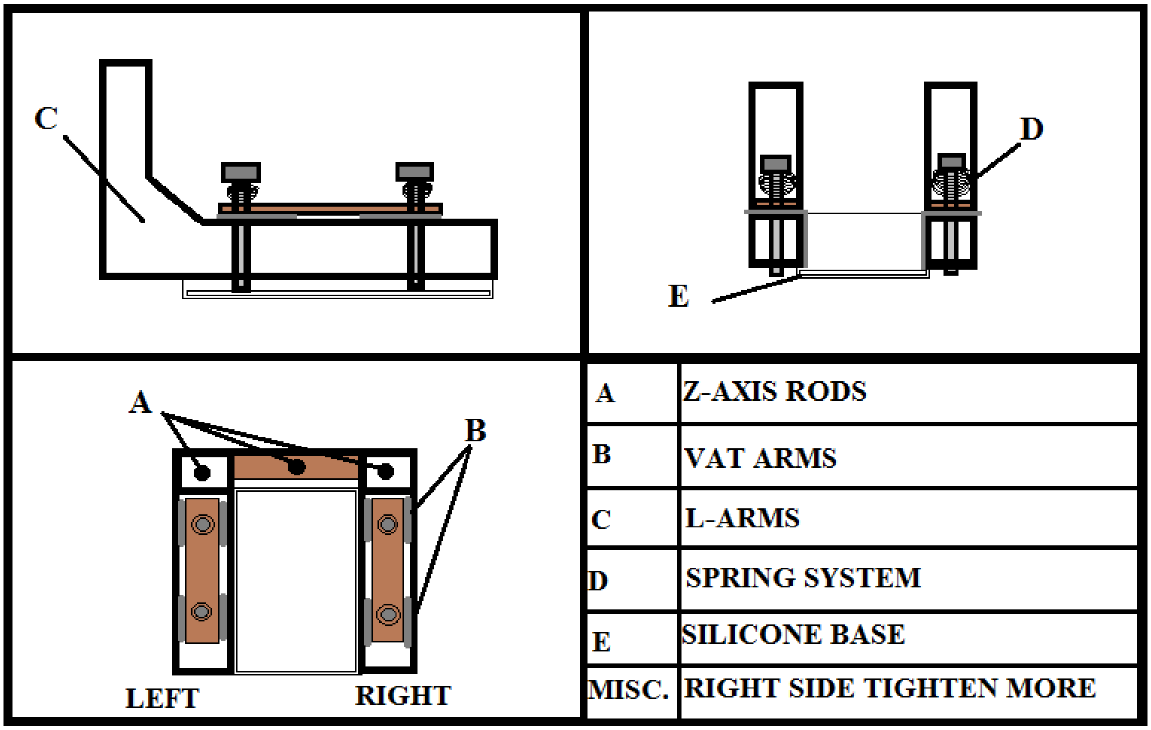

Figure 3 Passive Tilt Diagram

4 EXPERIMENTAL METHODOLOGY

4.1 MATERIALS USED

4.1.1 Construction Parts:

- 1 -11” x 4’ x ¾” Pine Boards
- 1 -5.4” x 2 x ¼” Pine Board
- 1 -11” x 2’ x ¾” Oak Board
- Wooden frame from MakerBot LETUBOT v4
- ? -1” wood screws
- 2 -L-arms from MakerBot LETUBOTH v4
- 2 -L-arms from Replicator2X
- Wooden frame for L-arms from MakerBot LETUBOT v4
- 2 -T8 8mm backlash proof nuts from MakerBot LETUBOT v4 and Replicator2X
- 1 -T8 8mm x 1000mm Lead Rod
- 1 T8 8mm x 300mm Lead Rod
- 2 -5/16x 4’ Smooth Steel Rods
- 2 -5/16 smooth rod endstops from MakerBot LETUBOT v4
- 1 - Moons’ Stepping Motor, p/n 17HD4OO1-28N
- 1 -LC4500-UV projector with Green BeagleBone
- 1 -2” diameter 45° mirror

4.1.2 Programming

- LC4500-UV with BeagleBone Green
- A4988 Driver Board w/ heat sink (should be included)
- Arduino Uno
- External adjustable power supply capable of a range of at least 10-20V
- Connectors:
    - Digi-Key 455-1162-ND (connector to step motor)
    - Molex 51021-0600 (mate connector to LC4500 connector J7)
- Headers:
    - 2 -Mouser 517-9601086303AR
    - 2 -Single row double sided header pins, at least 6 pins long
- Cables:

- 26-gauge wire (46 inches total)
- 22-gauge wire (12 feet total)
- 12V power supply (for LC4500-UV)
- USB-B (for Arduino)
- Either Ethernet or micro-USB (for BeagleBone)

4.2 CONSTRUCTION PROCESS

4.2.1 Structural

- The x, y, and z axis along with the extruder system and fan system was removed from the MakerBOT LETUBOTv4. The same process was done to the Replicator 2X, and the build plate platform was disassembled to collect the two L-arms that support the platform.
- The LC4500-UV projector and 45° mirror was connected to a stationary elevator block and then to the 5 ⅖' x 2' x ¼" wooden board. The projector will remain stationary while the mirror is adjustable for calibration. This piece will detach from the platform for the projector, which is the platform from the MakerBOT LETUBOT v4 without the build plate.
- The DLP build plate was constructed from an 11" x 2' x ¾" oak board that has had (3) ½" x ¼" holes in the back that lines with the three blots in the top back of the MakerBOT LETUBOT v4 and (2) 5/16" round holes 6" apart from each other, 3" from the center of the board, for the z-axis rods.
    - A pine board cut to the size of 4 ½" x 6" x ¾" was screwed into the middle of the pine board with (3) 1" wood screws in a triangle formation.
    - The anodized aluminum was cut to 4 ½" x 7 ½" x .2" and placed on top of the pine board. (3) 3mm x 30mm screws were connected from the build plate going around the pine board into the oak board. Lock washers secure the aluminum side and a washer and a nut secure the other.

4.2.2 Step Motor

- The z-axis is constructed from a quadruple-start 300mm lead screw with a pitch of 2mm for the Figure 10 Prototype , and a single-start 1000mm lead screw with a pitch of 2mm for the Figure 9 Original Prototype Design. They are moved by the stepper motor which would rotate in the positive and negative direction to move the structures both up and down. The voltage of this motor can range from 8V to 35V depending on the load. The lead screw is connected to both the vat and the projector structure by a backlash-proof nut connecting to the L-arms which supports both entities.

- The size of the lead screw can be switched by disassembling the motor by first unscrewing the four screws on the bottom of the motor and then pounding the end of the lead screw on a hard surface. That will disconnect the top part of the motor with the bottom part. After that the top part and bottom of the motor can be removed as well as the sleeve holding it in place from the lead screw. The only part that should remain on the lead screw now should be the rotational magnet. That can be removed by taking two pairs of pliers and placing one on the lead screw and the other on the rotational magnet with cardboard in between to protect both the lead screw and the magnet. Rotate both in opposite directions until the glue breaks off of the rotational magnet and it can slide off the lead screw.
    - When switching rods be sure to note the distance from the bottom to the rotation magnet. It should usually be around 8mm. The rotational magnet will need to be placed in the exact same spot on the new lead rod as the previous one, and the glued into place. Once the glue has cured, ensure it is completely solid. A resin based glue is recommended because of the bonding properties it possesses.
    - Reassembly is the opposite of the disassembly when the rotational magnet is connected to the new lead screw. Slide the sleeves that go on the top and bottom of the motor back into place, and then place the top and bottom pieces of the motor back into place. Finally, screw the four screws back into the bottom of the motor.

4.2.3 Vat and Spring System

The L-arms collected from the Replicator 2X were reused to support the Plexiglass vat, and are used as part of the spring system. This is described more in Figure 4 Vat Arms Design. The vat is a transparent, 5"x 8"x 2" Plexiglass container that is designed to contain the photoreactive resin for SLA printing. The top is uncovered, and there are two handles, one on each 8" side. The vat rests on top of the L-arm assembly using these handles. The handles are pinned to the L-arm assembly by two thin wooden slats. The slats have two drilled holes to thread through the two screws on each L-arm, one on either side of the vat handle. The slats are secured by a wing nut.

The passive tilt system works in this prototype by placing a spring between the wooden slats and the wing nuts. The wing nuts are tightened to different strengths depending on the side of the vat assembly; one side is tightened more than the other. When the vat pulls away from the build plate, the passive tilt system redistributes the applied force to the cured layer, allowing a peeling action to take place. A 5”x 1 ½” x 1” block of wood attached to the back end of the L-arm assembly houses the lead screw anti-backlash nut. This allows the lead screw to control the vat assembly’s z-axis motion.

4.2.4 Vat Floor

The vat floor is composed of a layer of Sylgard 184, which is a colorless silicone elastomer. It is used in this printer to prevent the resin from curing directly to the vat floor. This component of the printer is classified as a consumable, as it wears out over use. It must be replaced when the growing opacity interferes with print precision. Sylgard 184 is delivered in two parts and has a 10:1 mix ratio.

To install:

1. Calculate the needed volume of PDMS to create a 1 cm layer for your vat.
2. Sylgard 184 has a 10:1 mix ratio. Determine the needed quantities for your vat and measure each component in an appropriately sized graduated cylinder. Mix the two components together in a container well. You should see small air bubbles trapped in the elastomer.
3. Place the mixed elastomer in a larger container that has a lid. Fill the larger container with Refrigerant R-134a, taking care to contain the denser gas in the larger container. When the container is full, the pitch of the dispensing refrigerant should change and become lower. Close the lid carefully and wait for approximately 15 minutes. The refrigerant is denser than air, so by doing this, the small air bubbles trapped in the elastomer from the mixing stage will be pressed out. Add more refrigerant as needed.
4. Clean the interior of the vat. After the vat has dried, pour the elastomer into the vat, taking care to reduce air entrapment.
5. Place the vat on a level surface and cover the top with a lid to prevent dust or other particles from falling in. Allow the elastomer 48 hours to cure at room temperature. The cure can be accelerated by placing the elastomer in a heated environment.

Refer to the product information sheet on Dow Corning for further information. An example of the curing process can be viewed at: https://www.youtube.com/watch?v=DhC_5Zxtl3k&t=1s

4.3 FIGURES AND INFORMATION

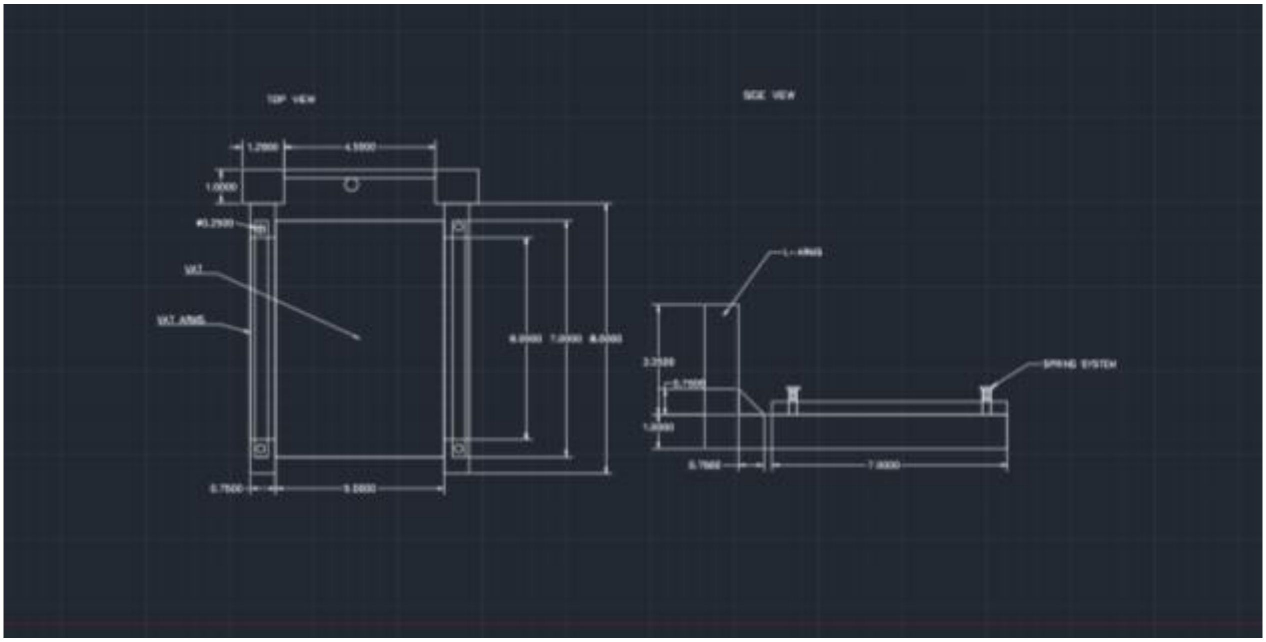

Figure 4 Vat Arms Design

4.3.1 Vat Arm Design and Construction

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The vat is built from Plexiglass with four springs on each corner of the vat. The springs are connected by drilling holes beside the L-arms and Plexiglass handles, inserting a screw in each hole, and clamping the handles down with a wooden slat which is threaded through the same screws. The springs are threaded through the screws and capped off by wing nuts. The springs on one side are tightened more than the other side. As the vat moves downward after each layer is cured, the springs create an unequal distribution of forces, breaking the vacuum between the resin and the vat floor which is created during the curing of each layer. The nut that is connected to the Z-axis is connected by a wooden block drilled into the plastic back of the L-arm assembly. Because wood is not an ideal medium to drill (4) 3mm x 30mm pilot holes a few millimeters from the lead screw nut's drilled passage, in this prototype, the lead screw nut was attached to the wooden block in an alternate way. The lead screw nut's passage was drilled with a slightly too small drill bit. The hole was widened slightly using a file, and the lead screw was hammered into its housing. In the final design for the prototype, the L-arm's themselves were turned upside down to shorten the distance from the vat to the build plate; however, the relevant vat mechanisms were flipped as well to remain in their correct orientation.

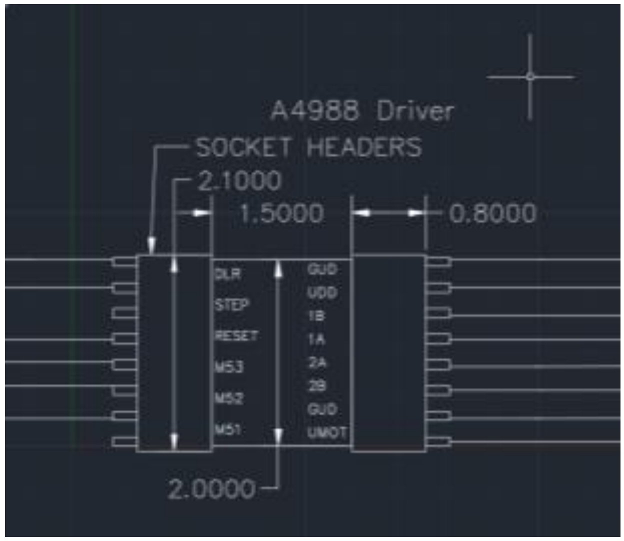

Figure 5 A4988 Wiring Section View

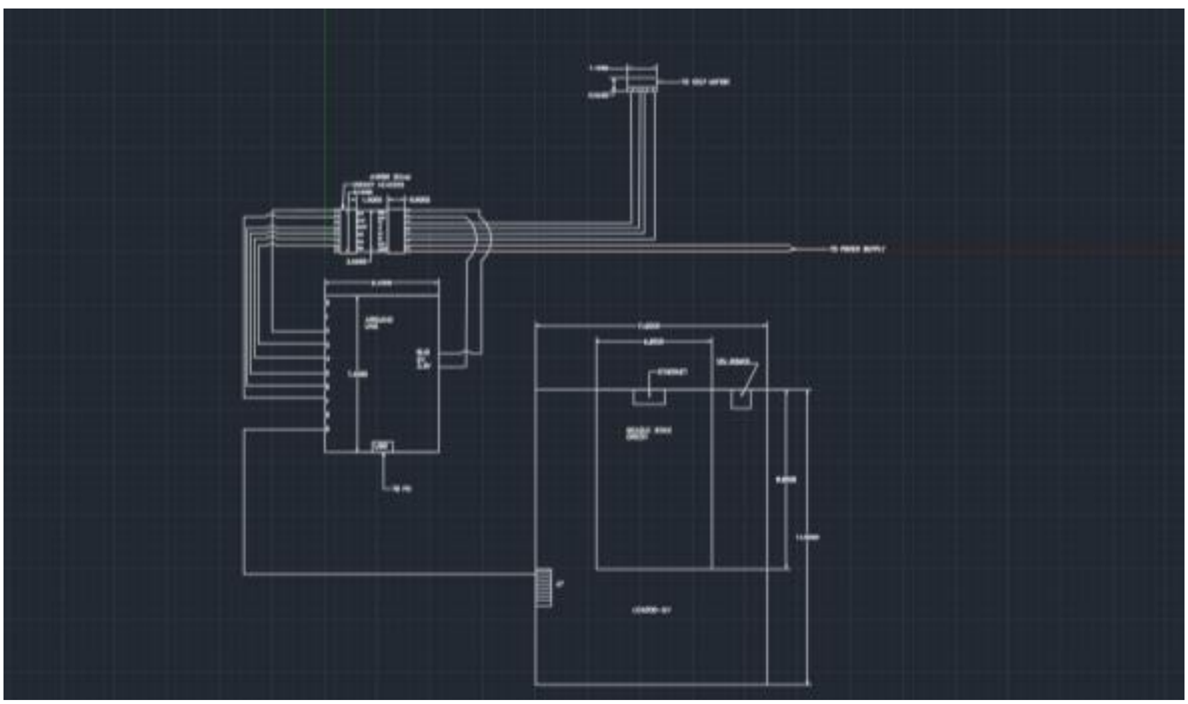

Figure 6 Wiring Diagram

4.3.2 Wiring and Programing Information

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The printer control system consists of an Arduino Uno, an A4988 driver board, and the LC4500-UV. The user controls the printer from a PC using the LC4500_GUI-PEM and the Arduino's serial monitor. The A4988 drives the stepper motor which moves the vat/projector assembly along the Z-axis. After the projector has been configured with the correct pattern sequence using the GUI, the serial monitor is used to configure the printer hardware and to start printing.

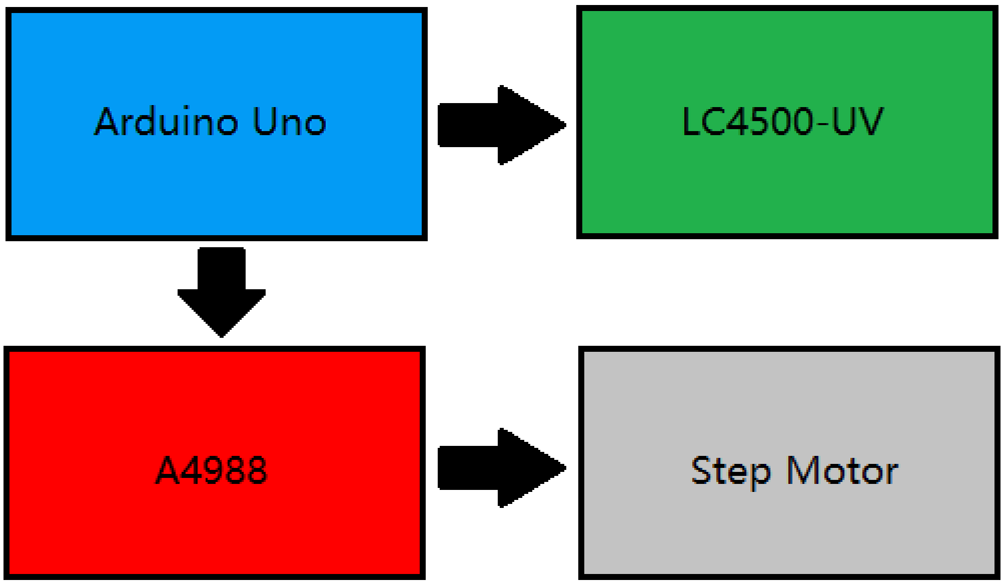

Figure 7 Control System Block Diagram.

4.3.2.1 The Arduino Uno

The Arduino Uno provides the highest-level control of the printer by running software which drives both the A4988 and the LC4500-UV by sending synchronized signals to both devices based on user input. The Arduino can be fully powered and run with a single USB cable connected to the PC. Along the top of the board are a number of headers which the software configures for digital logic output. These headers can be easily wired to the header pins on the A4988 driver, and to connector J7 on the LC4500-UV. The Arduino also outputs 5V power, which is used to power the A4988 driver.

Once the software has been uploaded onto the Arduino, it begins to run when the board is powered. To interact with the board, connect it to a PC over USB and run Arduino.exe (Arduino must be installed on the PC). Using the tools menu, ensure the port is connected to the Arduino, then open the serial monitor (Ctrl+Shift+M). This window displays all serial output from the program and provides a channel for user input.

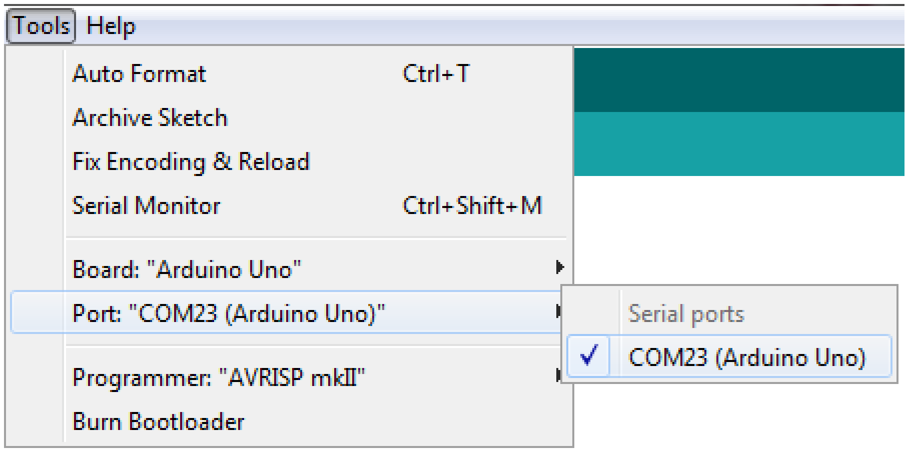

Figure 8 SWG Arduino COM Setup

4.3.2.2 The A4988 Driver

The A4988 driver board controls the stepper motor and has 16 total pins, comprising 8 logical inputs, 2 sets of power inputs, and 4 outputs which drive a single motor, as follows:

- Direction – controls the direction of movement of the motor.
- Step – causes motor to move one step.
- Sleep – puts board to sleep, minimizing power usage. Held high by a pullup resistor.
- Reset – resets motor and step size. Needs to be set high when running the motor.
- MS3, MS2, MS1 – these pins work in conjunction to set the step size.
- Enable – enables the motor to run. Held low by a pulldown resistor.
- VDD/GND – 5V power for board logic.
- VMOT/GND – motor power (up to 35V).
- 1A, 1B, 2A, 2B – these pins drive the motor.

This can be viewed by referencing Figure 5 A4988 Wiring Section View. Each of the logical inputs and the 5V power supply are connected to Arduino outputs. Pins 1A, 1B, 2A, and 2B must be wired to a connector (Digi-key 455-1162 ND) which attaches to the step motor. VMOT must be powered by an external power supply which must not exceed 35V and 2A. The A4988 must have a heat sink attached to prevent overheating.

4.3.2.3 The LC4500-UV

The LC4500-UV displays UV patterns in sync with motor movement, with each pattern corresponding to a single build layer of the print. These patterns should be sent to the projector as a single pattern sequence, with solid black patterns inserted between each cure pattern, including the first and last patterns in the sequence. The black patterns will be displayed during the peeling and vertical movement stages of printing. The Arduino sends a trigger signal to pin 4 of connector J7 on the LC4500-UV. The projector advances to the next pattern in the sequence on rising edges of the trigger signal. Thus, the pattern sequence must be setup for external (+) trigger mode and must already be running before the print job is started.

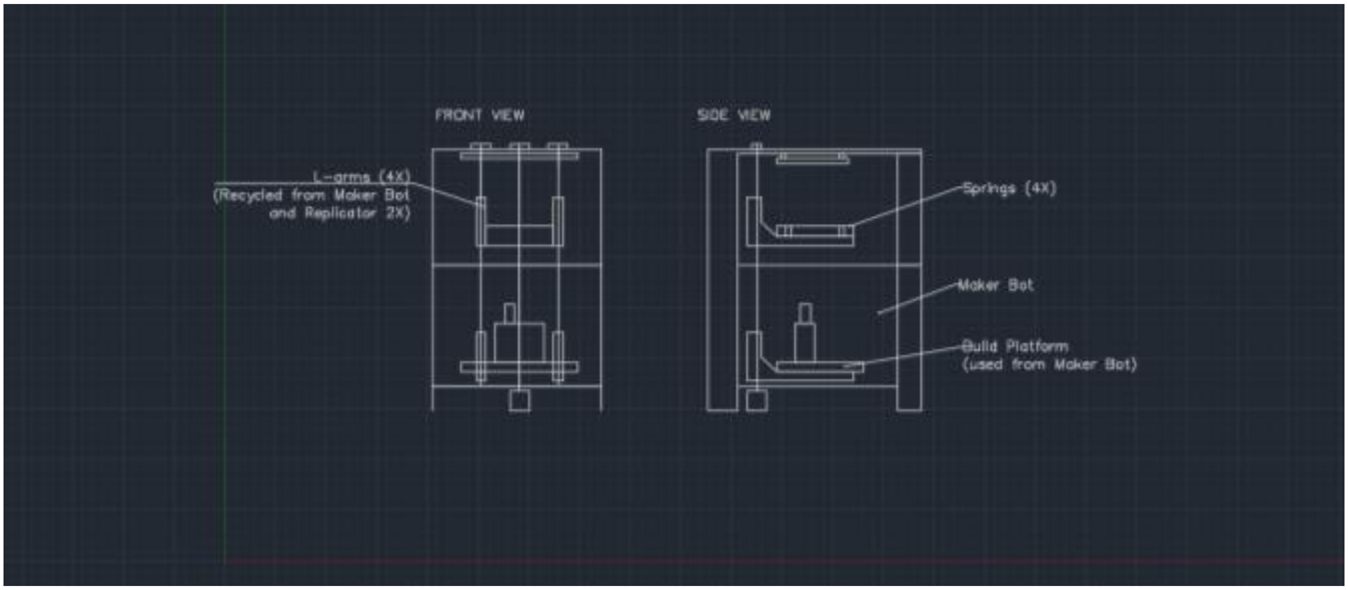

Figure 9 Original Prototype Design

4.3.3 Original Prototype Information

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The prototype was to be constructed from the original MakerBOT LETUv4 and for it to be extended upward to allow for a larger z-axis to allow for larger DLP prints. The bottom-up printer would be construed by placing the build plate at the top of the structure. Then the vat which contains the resin would relate to the projector and would move up and down along the z-axis. The projector orientation was changed for the new printer to be faced horizontal instead of vertical to allow for a larger z-axis. This can be seen in Figure 10 Prototype .

4.3.3.1 Vat and Projector Structure Distance Calibration

The vat and projector move in unison along the z-axis. By using the same lead screw for both the vat structure and the projector structure, they move as one unit and will remain at a set distance, as one cannot move without the other moving. Calibrating the distance between the two structures will have to be done before connecting them to the z-axis, and it can be done by putting each one on and then measuring out the steps for the rod to rotate before screwing on the next piece. The lead screw has a pitch of 2mm, so the distance between the vat and the projector structure must be a multiple of 2mm. Additionally, because the lead screw has four distinct threads, one full revolution equates to 8mm of vertical movement. Thus, once attached to the lead screw, the projector and the vat may only move in increments of 8mm relative to each other. When assembling and calibrating, be sure the nuts are oriented correctly in relation to one another.

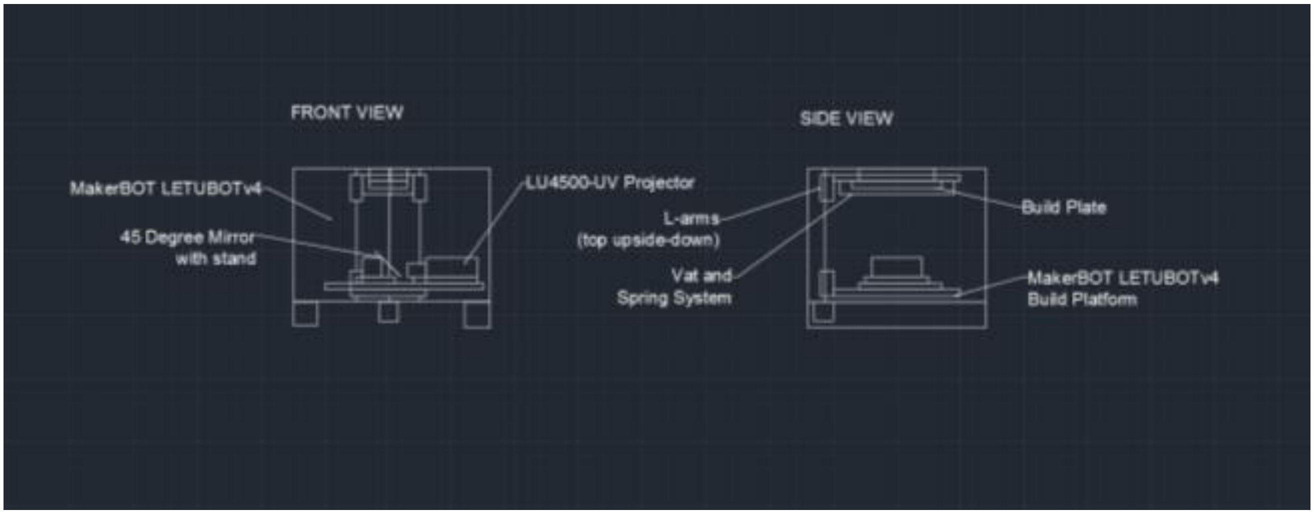

Figure 10 Prototype v1.0

4.3.4 Prototype v1.0 Information

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The prototype v1.0 is an adaption of the original prototype; its specific purpose is to test the curing and peeling processes and to check for flaws in the hardware and software. Rigorous testing with this prototype will determine unknowns such as cure time, projector power level, effectiveness of the peeling system and multi-layer curing, durability of the control system, and more. The resulting information will be incorporated into the design of v2.0.

4.3.4.1 Mirror orientation

The platform for the projector is adjustable to account for the ability to change the mirror. The mirror should be at 45°. If not at this angle then the mirror’s angle can be changed with a 3.5 sized Allen wrench. With this angle, the mirror should be placed directly under the vat, so the UV that it emitted from the UV projector could be reflected directly upward to the vat.

4.3.4.2 Projector and Mirror leveling

When lined up to face each other the projector is shorter than the mirror, so leveling the two to fit along the same z-axis is required. This is done by attaching a wooden block to the bottom to both the projector and the mirror. Then by turning on the projector the accurate distance between the projector and the mirror can be acquired. This is done by once checking that all four corners of the projector screen are shown to fit on the vat the length and width of the screen can be adjusted to be larger or smaller by moving the mirror and the projector closer or farther away from the vat. Finally, the blocks that are connected to both the mirror and projector are connected to the platform. The platform is the adjustable part.

5 USING THE PRINTER

5.1 HOW TO PRINT

5.1.1 Overview

This printer creates 3D objects by printing layer-by-layer. Each layer is created when the LC4500-UV displays a unique PNG file corresponding to the appropriate cross-section of the object, curing resin in that specific pattern. These PNG files can be created by slicing an STL file using free slicing software available from FreeSteel. The resulting images can then be organized in a pattern sequence which the LC4500-UV will display in sync with the printer hardware.

5.1.2 Slicing STL to PNG

To create the requisite PNG files to use in the printer, first download and install these programs:

- Slic3r - http://slic3r.org/download
- Slicing software from FreeSteel – http://www.freesteel.co.uk/wpblog/slicer/
- Python 2 – https://www.python.org/downloads/release/python-2712/

After installing Python 2, the install directory must be added to the path. From My Computer, open properties, then Advanced System Settings, then Environmental Variables. Edit the PATH variable to include the path to the directory where Python was installed.

For each print, first create an STL file containing the design to be printed. This STL file must then be flipped along the Y-axis because the slicing software also performs a Y-flip. Open Slic3r and click Add… in the upper left corner. Browse for your STL file and open it. When it appears in the main window, right click on the object and select Flip -> Along Y-Axis. Then right click on it again and select Export Object as STL to save the flipped object as a new STL. This is the STL which will be sliced into PNG files. Once the STL is ready, run slicer.py, a script provided by Keynote which runs the FreeSteel slicing program. This script must be run from the command line with the following arguments, space-separated:

- The name of the STL file to be sliced (required)
- The location of the STL file to be sliced
- The directory where the resulting PNG files will be placed

Only the first argument is required. The two path arguments are optional; if left blank, the current directory is used. Note that because the command-line interface is space-delimited, no filename or path may contain spaces. To avoid the tedious process of using the command line interface and typing these arguments each time the slicer is run, Keynote has also created a batch file (slicer.bat) as a wrapper for slicer.py, which contains variables corresponding to the python script's arguments. These variables can be set using a text editor before running the batch file. The batch file contains one extra variable which is used to specify the location of slicer.py. Like the other path variables, if this is left blank, the current directory is used. Again, no filename or path may contain spaces.

Once slicer.py starts running (either from command line or using slicer.bat), a progress bar is displayed in the run window. Depending on the size and complexity of the source STL file, the slicing process may take several minutes. At its conclusion, a new directory with the same name as the STL source file is created in the specified output location. This directory contains all of the resulting PNG slice files, sorted by their Z-position from low to high. These images are now ready to use in the pattern sequence which will run during the print.

5.1.3 Arduino Software Guide

The Arduino software provides a simple interface which is used to setup and start the printer. At startup, the program displays its internal settings for reference. The optimal values for these settings have been determined through prototype testing and are hard-coded into the software. These values may only be changed by editing the source code, which is not recommended. These parameters are as follows:

- Layer thickness = 0.40mm
- Exposed curing time = 3.00 seconds
- Peeling distance = 0.60mm
- Peeling/prep time = 40.00 seconds

As one of the goals for this prototype is to increase the speed of 3D prints, great care has been taken to reduce the time required to cure and to peel each layer. The resin requires 3 seconds of UV exposure to cure fully. The limiting factor for peeling is the specifications of the lead screw and the capabilities of the hardware. This prototype uses a lead screw which must turn 25 full steps to achieve a vertical rise or fall of 1mm. The hardware can only process one full step per second. Using a peeling distance of 0.6mm, the vat/projector setup must first lower 0.6mm to peel, then raise 0.2mm to be in place for the next layer. The net displacement is 0.4mm, equal to the height of one layer. The total distance traveled is 0.8mm at 25 steps/mm and 1 second/step, so the total peeling/prep time = 20 seconds. The total time required to print = the number of layers * 23 seconds.

After displaying the internal settings, the software prompts the user for the number of layers to be printed. This is the only value that the user may change, and it must be set correctly for each print. This value should be set to the number of PNG files created by the slicer software. Once this value has been set, the user has the option to change it or to start printing.

As the printer prints, the Arduino software displays information about the status of the layer currently being printed, including an estimate of the time remaining. A print job may be paused or aborted between layers; however, note that this may have disastrous cosmetic or structural consequences. Once printing concludes, another print may be started at any time. When printing a new design, be sure to set the number of layers and use the correct pattern sequence.

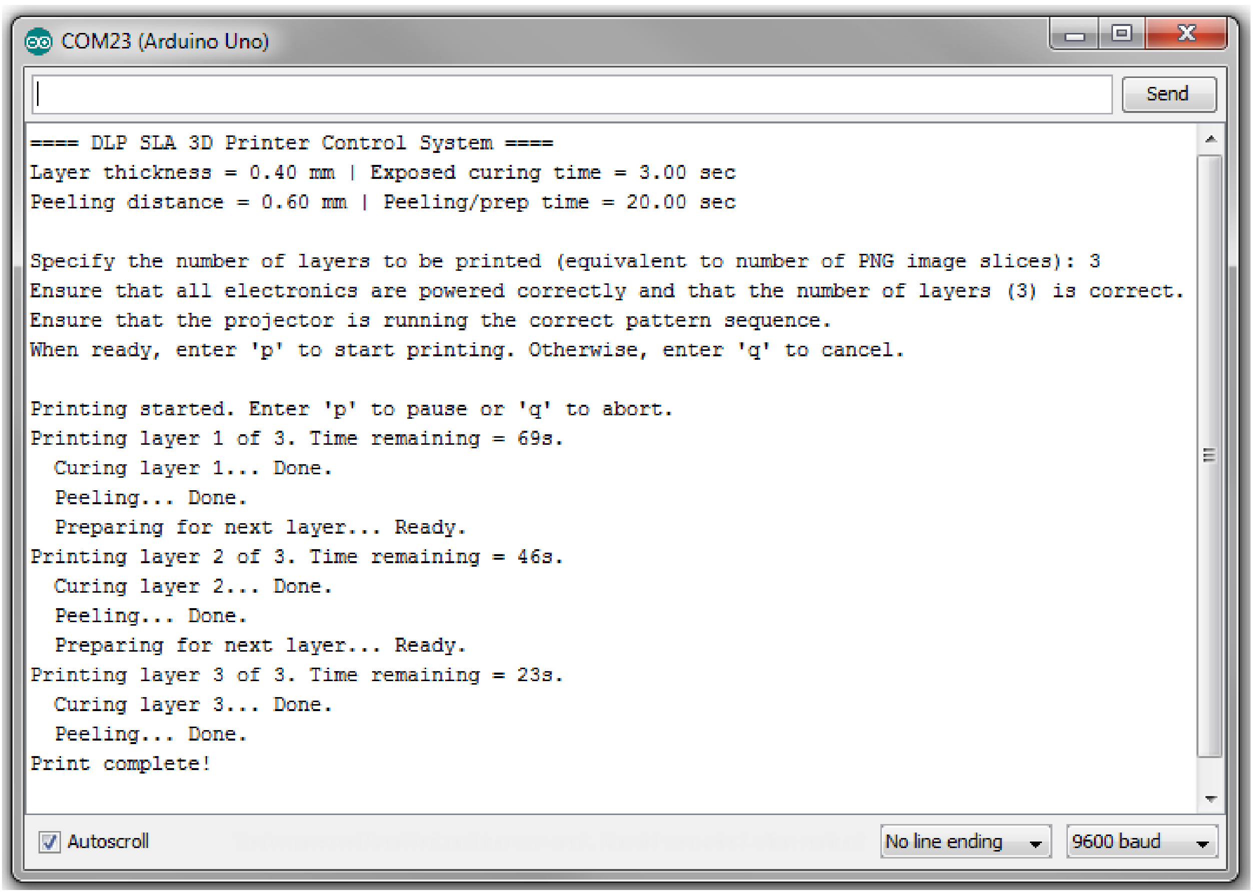

Figure 11 SWG Complete Print

5.1.4 Running the Printer

To print an object, follow these steps:

- Ensure that all components are connected properly as shown in the schematic.
- Power on the LC4500-UV and connect to the PC via USB or Ethernet, using the LC4500_GUI-PEM. For more information, refer to the LC4500 User's Guides.
- Power on the Arduino Uno by connecting it to the PC via USB. Open the serial monitor.
- Verify that the external power supply is set to the proper levels, then power it on.

- Create a pattern sequence (or use a saved solution) and send it to the LC4500-UV using the GUI, abiding by the parameters outlined in section 4.3.2.3. Start the pattern sequence.
    - (INSERT USER GUIDE LINK)
- Use the serial monitor to configure the print settings and start the print job, as described above.
- Do not disturb any of the electronic or structural components while printing is in progress.

5.2 TROUBLESHOOTING

5.2.1 Prototype v1.0

After initial construction, a few initial problems with the projector could be initially seen on the mechanical side of it.

5.2.1.1 Base Plate Block Trimming

When the top of the printer was placed on it was immediately visible that that build plate structure didn't fit inside of the vat. This was because the wooden blocks that drop the build plate down into the vat. This was fixed by trimming and then sanding the wooden blocks to be smaller than the build plate to allow it to fit into the vat.

5.2.1.2 Realigning for Vat Misalignment

The next problem turned out to be that the vat was not aligned to be center to the projection or with the printer itself, so build plate structure must move to the left 15mm to allow for the misalignment. This was done by moving the holes to allow for the lead rods to go through over the 15mm. By doing this it could fix that problem.

5.2.1.3 Mismatch Vat Height

When viewed from the front the left and right sides of the vat was different. The left side had a height of 2in while the right was 2 ¼in. Also with gravity acting on the vat, and the holes in the l-arms that attach it to the lead rods being a size too big- the front is lower than the back. This problem is fixed by placing wooden stilts on the front two metal vat arms. To compensate for the difference in the left to right height there are two wooden blocks on the left side and three on the right.

5.2.1.4 PEM_GUI

The printer works with the latest version of this soft wear which can accept and output PNG files.

6 EXPERIMENTAL RESULTS AND DISCUSSION

6.1 RESULTS OF EXPERIMENT PROTOTYPE MINI

The first prototype that was tested was the prototype v1.0. Its main purpose is to test the theory of that changing the object of motion from the baseplate to the vat will have an adverse effect on the print. Before that, a series of tests must be conducted to verify that the curing of the resin works, that it can stick to the baseplate, and then it can cure to the baseplate through the vat.

6.1.1 Test 1

The purpose of the test was to see if resin can cure to the baseplate in its original position when the printer is fully assembled. Resin was exposed to a blank UV image for one minute. The resin cured in a thick layer that distinctly warped around the edges. The warping was localized 0.5mm from the edge of the build. There were visibly distinct layers cured together. This behavior is thought to be the result of thin layers curing to the build plate, but because they are long and thin, the cured resin warped significantly and peeled off the plate. The layer then floated off slightly in the resin allowing more resin to collect beneath it. The projector continued to cure layers underneath the first layer which adhered to the previous layers until the experiment ended.

The result of this experiment was a build consisting of a thick collection of multiple layers which adhered strongly to the build plate. The dimensions of the cured build were 80mm x 125mm. The gaps present in the build are due to the trapped air between the Sylgard coating and the build plate.

6.1.2 Test 2

This test was conducted in order to find the minimum amount of time needed to cure the resin without having it warp and peel off the build plate. The resin was exposed to a blank UV image for 15 seconds. In this print trapped air bubbles caused circular gaps that formed in the build layer. The print did not stick to the plate at all, and it was found floating in the resin when the vat was removed from the printer. The layer of this print very thin, with a thickness of approximately 0.4mm. The warping of this print was significant, extending 15mm into the layer at some points. There is only one distinct layer visible.

6.1.3 Test 3

The resin was exposed to a blank UV image, but the exposure time was chosen as 37 seconds because a minute exposure was too long and 15 seconds was too short. The projector was offset which caused significant warping of the two edges that hung off the build plate. There were three distant layers visible in this print. Apart from the warped edges, this build demonstrates good cohesion throughout. The vat is not at a true parallel to the projector image and to the build plate. The inconsistent distance and exposure to the UV causes inconsistent layer thickness. The build thins as it moves towards C1. At C1, the thickness is 0.44mm, while at C3, the thickness is 0.6mm. This print adhered well to the build plate, although the warped edges may have curled around the build plate and been a contributing factor. Further testing is required to confirm this.

6.1.4 Test 4

This test attempted to create a complete, continuous layer by exposing checkerboard image for 30 seconds, and then inverting the image for another 30 second exposure. The size of the print is 80mm x 125mm. Distinct checker patterns are visible along C1C3 and C3C4, but the build smooths into a continuous layer as C1 is approached. Each checker in the pattern have slightly warped edges which interfered with the continuous layer cure. This issue is less pronounced as C1 is approached. The warping of the build is the main problem. At C3: 1.3mm; at C1: 0.87mm.

6.1.5 Test 5

This test attempted to cure 30 layers of resin in a checkerboard pattern, exposing each layer for 15 seconds. The build appears to have adhered to the build plate for at least 2/3 of the print, given that the build layers appear significantly more offset 2/3 into the build. It appears to have disconnected at that point and somehow continued printing. The build was adhered to the Sylgard coating at the end of the experiment. The individual checkers were slightly warped, but the effect was mitigated by the surrounding checkers and the addition of subsequent layers. The effect was more pronounced on the edges of the build, where there were no surrounding checkers to prevent significant warping. The bubbles of air trapped between the build plate and the Sylgard reduced the amount of resin cured in the first few layers, reducing the amount of surface area and reducing the adhesion between the build and the build plate. Six thickness measurements were taken at random points around the build: 3.75, 3.25, 4.32, 4.2, 3.59, and 3.6mm.

6.1.6 Test 6

This test attempted to cure 15 layers of resin in a checkerboard pattern, exposing each layer for 15 seconds. The build did not adhere to the build plate. The effects of the uneven vat problem referenced in 6.1.3 are easily discernable in this test, as the lower side of the build is significantly thicker than the upper. It is also a crisper build, whereas the upper side checkers appear to melt into one another. The pulling speed is hypothesized to be too much for the first thin layers to handle and is pulling the build off the build plate. The air bubble issue was reduced in this test by scraping the froth off the top of the resin and carefully placing the build plate into the vat to avoid trapping air.

6.1.7 Test 7

This test, much like the previous, attempted to cure 15 layers of resin in a checkerboard pattern, exposing each layer for 15 seconds. However, in this test the stepping speed was increased to 100 milliseconds per step, whereas all previous tests were conducted with a stepping speed of 25 milliseconds per step. The set of the vat was altered to be more parallel to the bottom of the printer. These measures appeared to have no effect on the adhesion of the build to the vat, as the build was once again found floating in the resin at the conclusion of the test. The cause of this lack of adhesion is hypothesized to be due to a failure of the passive tilt system. The current bolts are too short relative to the size of the springs, so the springs are almost fully compressed when the vat is set in its original position. By increasing the length of the bolts, the springs can be given greater distance to compress. The passive tilt system will be able to work as it should, helping peel off build layers, instead of the build layer being pulled off the build plate all at once.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 GENERAL CONCLUSION

As an initial prototype, this printer was successful in fulfilling its purpose. The design team has learned valuable lessons about how to design 3D SLA printers that will be applied toward the design of the v2.0 printer. Chiefly, precision in both design and machining is of the utmost importance. The v1.0 achieved limited success in printing complex builds. The problems encountered in operating the v1.0 printer have led to the recommendations for the v2.0 printer outlined below.

7.2 RECOMMENDATIONS

- Add UV shielding
- Ensure that the vat and the build plate are parallel
- Increase L-arm stability
- Build a covering for the projector and electronic components to protect them from spilled resin
- Use less wood
- Use a smaller build plate support
- Add a software abort capability
- Use an active, rather than passive tilt system

References

1) "Best-in-class Combination Stereolithography 3D Printer Development Using DLP® Technology." *TIDA-00293 Best-in-class Combination Stereolithography 3D Printer Development Using DLP® Technology | TI.com*. Texas Instruments, 22 Aug. 2014. Web. 23 May 2017. <http://www.ti.com/tool/tida-00293?keyMatch=DLP%2B3D%2Bprinter&tisearch=Search-EN#Technical Documents>.
2) Holtrup, Reinout. *XZEED DLP*. Tech. N.p.: U of Twente, 2015. Web. 15 May 2017. <http://essay.utwente.nl/67685/1/Paper%20Exzeed%20DLP%20Reinout%20Holtrup.pdf>.

8 APPENDIX

[1] Texas Instruments Top-Down Printer design files: ..\Design Files\TEXAS INSTRAMENTS 3D DLP PRINTER