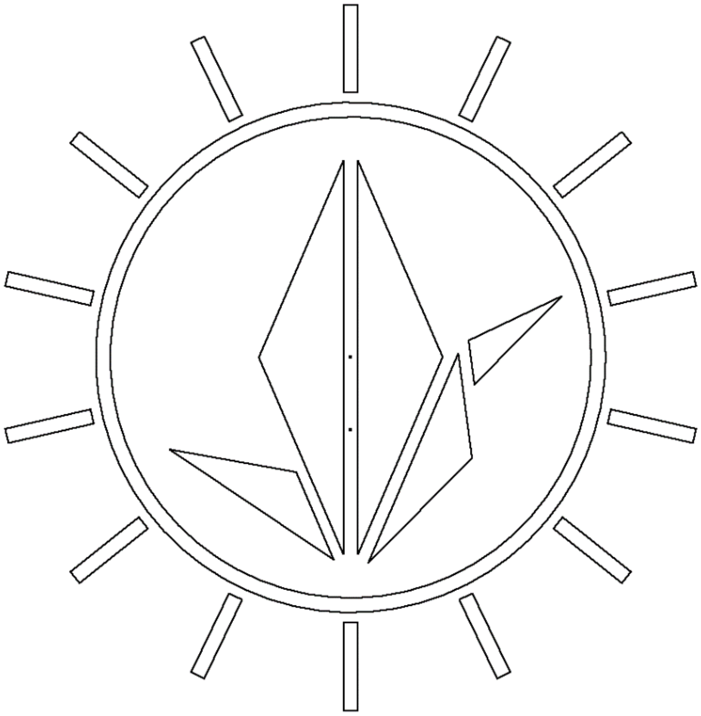
ME 4950: Design Cycle #4 Final Report

Team Solargami

March 1, 2018



Collapsible, Minimalistic Solar-Powered 3D Printer Project

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Section I: Introducing the Design Problem

Background

Additive manufacturing and rapid prototyping via 3D printing technology has become a big influence in the engineering field. The expanding capabilities and applications 3D printing has evolved into in the past decade has led to exploring the uses ranging from highly sophisticated research laboratories to terse and unpredictable terrain to commercial use by everyday people. In working with the United States Naval Surface Warfare Center (USNSWC) and their biochemist researcher, Dr. Josh Kogot, our team has been investigating the capabilities of creating a novel 3D printer system that exhibits innovative characteristics not readily seen in the current 3D printer market.

Purpose

The purpose of researching and developing a collapsible, minimalistic solar powered 3D printer comes with the intentions of use in remote and/or low resource regions such as in military operations or developing countries, where constant access to electricity is not always available. A low-cost component is involved with the intention of reaching a commercial consumer market. In having a 3D printing system that is collapsible, the element portability is added, which does not yet widely exist in the 3D printer market. Portability will be especially valuable in military settings as well as possibilities for in-space manufacturing. Solar power adds the element for manufacturing accessibility regardless of available power from surrounding infrastructure. Finally, a minimalistic design contributes to both low cost for an affordable price point in the commercial consumer market, while additionally requiring the printing system to be lightweight and thus, making transportability easier for the user.

Design Constraints

In the design and development of our 3D print system (Solargami), the design constraints included the following:

- Portable device with easy setup (collapsible, folding, and minimal parts)
- Operate on rechargeable batteries and solar-power
- Minimum print platform area of 8 cm x 8 cm
- Maximum weight of the system must be 10 pounds or less.

Design Problems to be Solved

The critical design problem to be solved is successfully creating a mechanical structure that can reach any desired position within a designated build envelope using a single pole dynamics system. In order to solve and develop a solution, a combination of translational motion of the major axes is required.

The methods for actuating the vertical and horizontal translational motions are solved and designed. Along with actuation, the second problem of a foldability and collapsibility is solved and designed. For this, mechanism for component modularity, re-orientation, and geometry are heavily analyzed, tested, and modified over many design iterations.

Electronics and software strategies for powering and controlling the Solargami is the other major component problem designed and solved in this project. The parameters of solar power dependency prompt strategies for operating both the mechanical and software functionalities in an energy efficient manner that is optimal. Software plays a major role in this as optimizing print path algorithms can drastically affect power output as well as energy usage of the actuation of the stepper motors in articulating the movements of the device.

In the following sections, the redesigned solutions to problems for Solargami solved during Design Cycle 4 will be discussed in further detail.

Section II: Design Choices and Justification

Comparisons with Current Products

The 3D Printer market has skyrocketed over the past decade as 3D Printers have become the new standard for rapid prototyping and manufacturing. With so many options and competing devices, it is both important and valuable to consider the things that currently exist and the innovations that are needed and not yet available when developing a new 3D Printer.

The following presents an analysis of Solargami compared to some of the best 3D Printers currently available on the consumer market:

	Dimensions	Weight (kg)	Min Resolution (microns)	Max Resolution (microns)	Power Usage (W)	Cost
Solargami	431 x 508 x 162 mm	4.3	To Be Tested	To Be Tested	22.07	$250
MakerBot Replicator	528 x 441 x 410 mm	22.8	100	400	150	$2,499.00
da Vinci Mini	390 x 335 x 360 mm	10	100	400	480	$198.00
Ultimaker 2+	342 x 493 x 588 mm	11.3	20	600	100	$2,499.00
Formlabs Form 2	350 x 330 x 520 mm	13	25	100	254	$3,350.00
M3D Micro 3D Printer	185 x 185 x 185 mm	1	50	350	150	$349

The MakerBot Replicator+ has excellent design and safety features. This desktop 3D printer is expensive, but it offers excellent print quality, and uses 1.75mm PLA filament. It's also user-friendly enough for home users to use - as long as your budget can stretch to the high asking price.

The XYZ printing da Vinci Mini is suitable for those who are looking for a budget 3D printer. It is one of the most affordable ways to get into 3D printing and its easy-to-use interface probably makes it the easiest. Although it is a budget model, it surprisingly produces good results and creates impressive 3D objects despite its price and size. In addition to that, the XYZ printing da Vinci Mini is a compact printer that makes it easy to store.

With fused deposition modeling, the Ultimaker 2+ offers amazing print quality, making it one of the best 3D printers for professional use. It is highly reliable and accurate when it comes to producing 3D models. However, it is expensive, and the fact that it is aimed at professional environments means it is not beginner-friendly.

The Formlabs Form 2 is a good 3D printer for enthusiasts who don't mind paying extra since it uses stereolithography (SLA) and Fuse 1 selective laser sintering (SLS) technology to get the very best print quality. It's a beautifully-designed 3D printer, and can be connected to PCs via USB, Wi-Fi and Ethernet.

The M3D Micro 3D Printer is cheap and an excellent 3D printer for beginners. The compact, cube, design means it can be easily placed within the home or office. Its print technology is fused filament fabrication, which produces poor print quality. Considering its size, it is only able to make small models.

Comparing Solargami to the 5 best 3D printers in 2018, it has relatively smaller dimensions and weight, except the M3D printer. The average power usage during printing for Solargami is around 22 Watts which is 5 times lower than Ultimaker 2+. Compared to Formlabs Form 2, MakerBot and Ultimaker, Solargami is affordable but costs slightly more than da Vinci Mini and M3D. Among the three printers, da Vinci Mini has the most similarities to Solargami where it is compact, low price and has an easy-to-use user interface. With the stated specifications and additional collapsible feature, we believe Solargami is able to compete with the 3D printers on the market.

Section III: Improvements and Modifications

System Overview:

Solargami is broken down into three system components: Mechanical, Electrical, and Software.

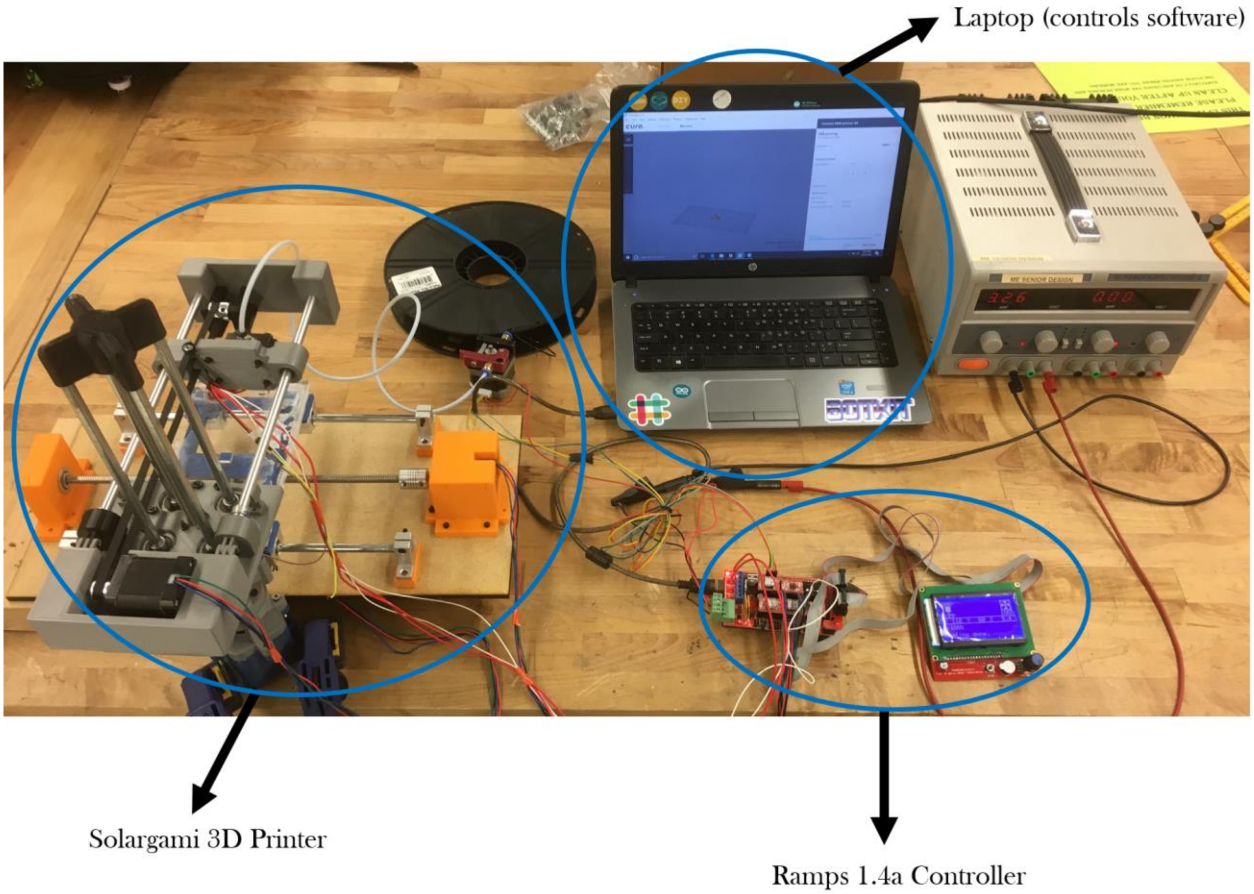


Figure 3.1: *Solargami System Setup Overview*

A. Mechanical

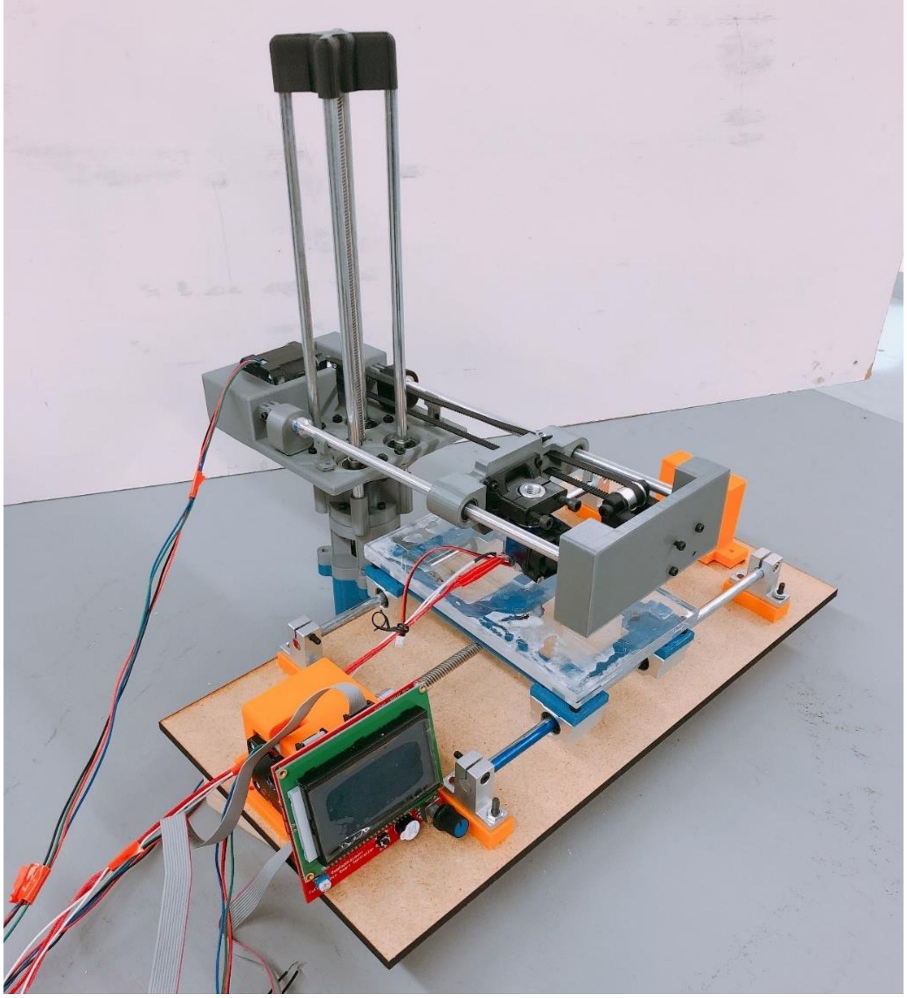


Figure A1: *Physical Design of Solargami System*

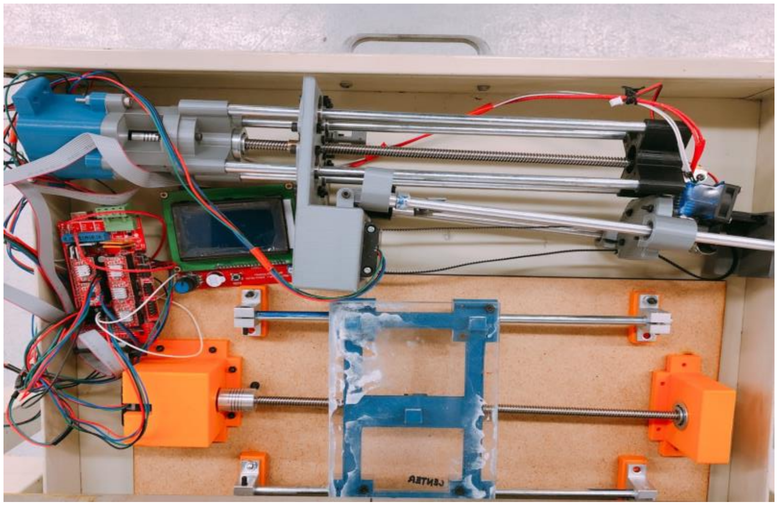


Figure A2: *Physical Design of Solargami System*

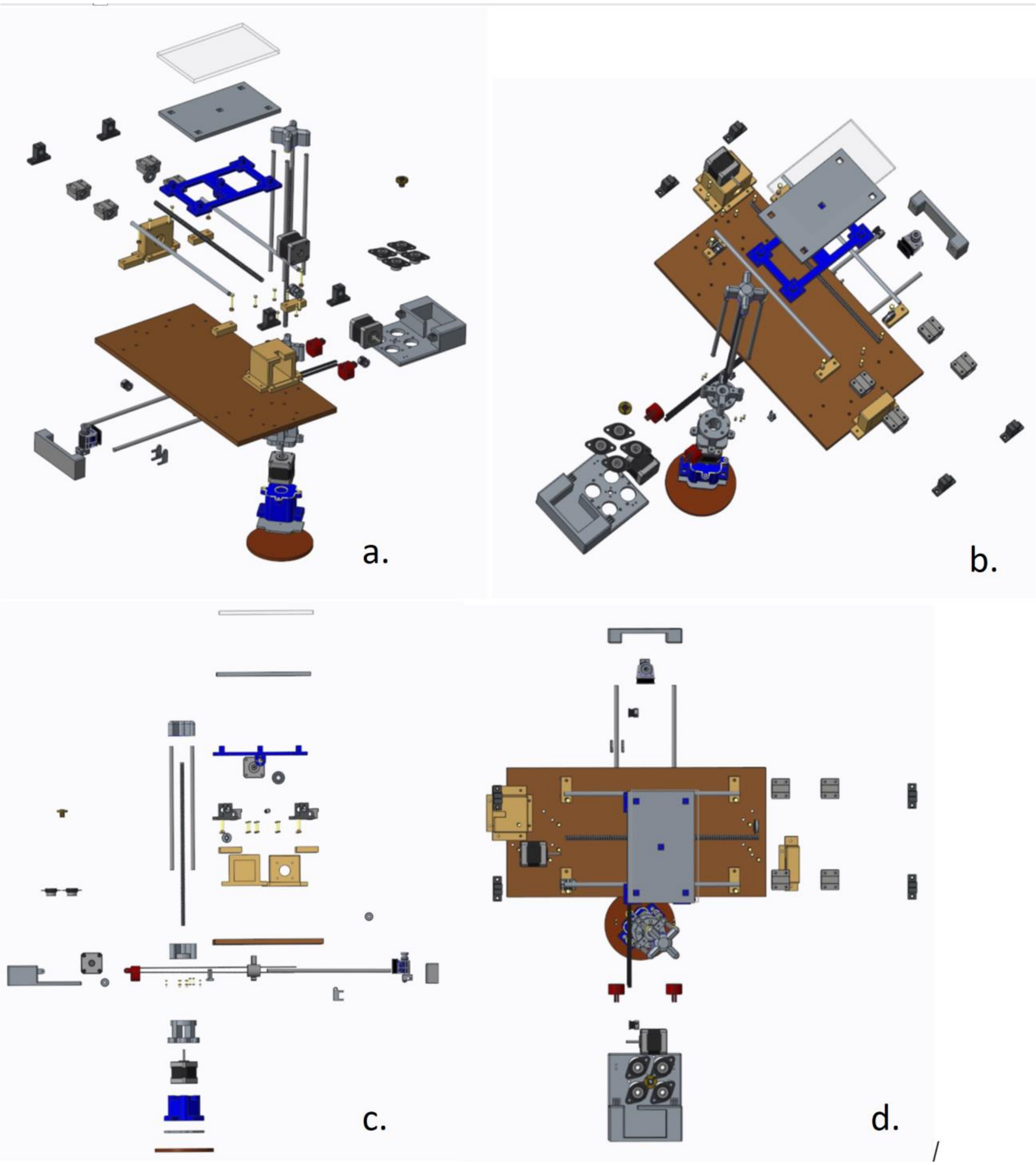


Figure A3: *Exploded View CAD of Solargami; a. isometric b. top isometric c. side view d. top view*

A1: Change of Coordinate System Operation

The biggest change from the previous Design Cycle was changing from a cylindrical coordinate system to the standard Cartesian xyz-coordinate system (**Fig. A2**). This decision was made after extensive discussion with Dr. Kogot about both the complexity from a software standpoint as well as uncertainty in the stability of a continuously rotating body from a mechanics standpoint.

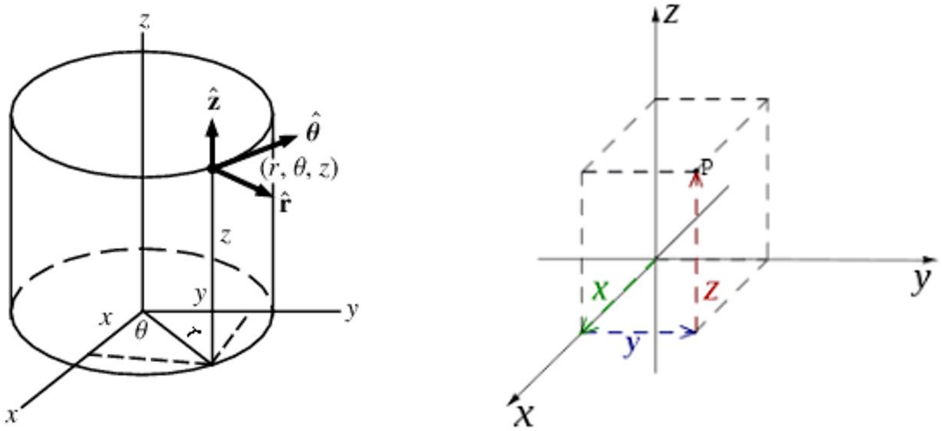


Figure A4: *Cylindrical Coordinate Space (Left) and Cartesian Coordinate Space (Right)*

Multiple attempts and changes were made to our base design to achieve stability, but none of the solutions produced improved results or success. With stability and energy conservation being central focus points, a new approach was needed. In addition to mechanical complexities, due to the polar coordinate system being extremely uncommon in 3D printing software, very limited open-source code was available to drive the printer in such a manner. The closest open-source code that was found involved a rotating print bed, as opposed to Solargami's design, which rotates the entire printer's body.

In order to solve this problem, it was proposed to separate the system into two components. The first component is the "actuation tower" (shown in **Fig. A5**), which includes all of the previous prototype's components except the rotation actuation components (vertical z-axis actuation via lead screw actuation, horizontal x-axis actuation, and extruder). The second component is the new actuating print bed (shown in **Fig. A6**) This print bed translates in the effective y-axis, which is orthogonal the actuation axis of the “actuation tower”. The new print bed is controlled by lead screw action.

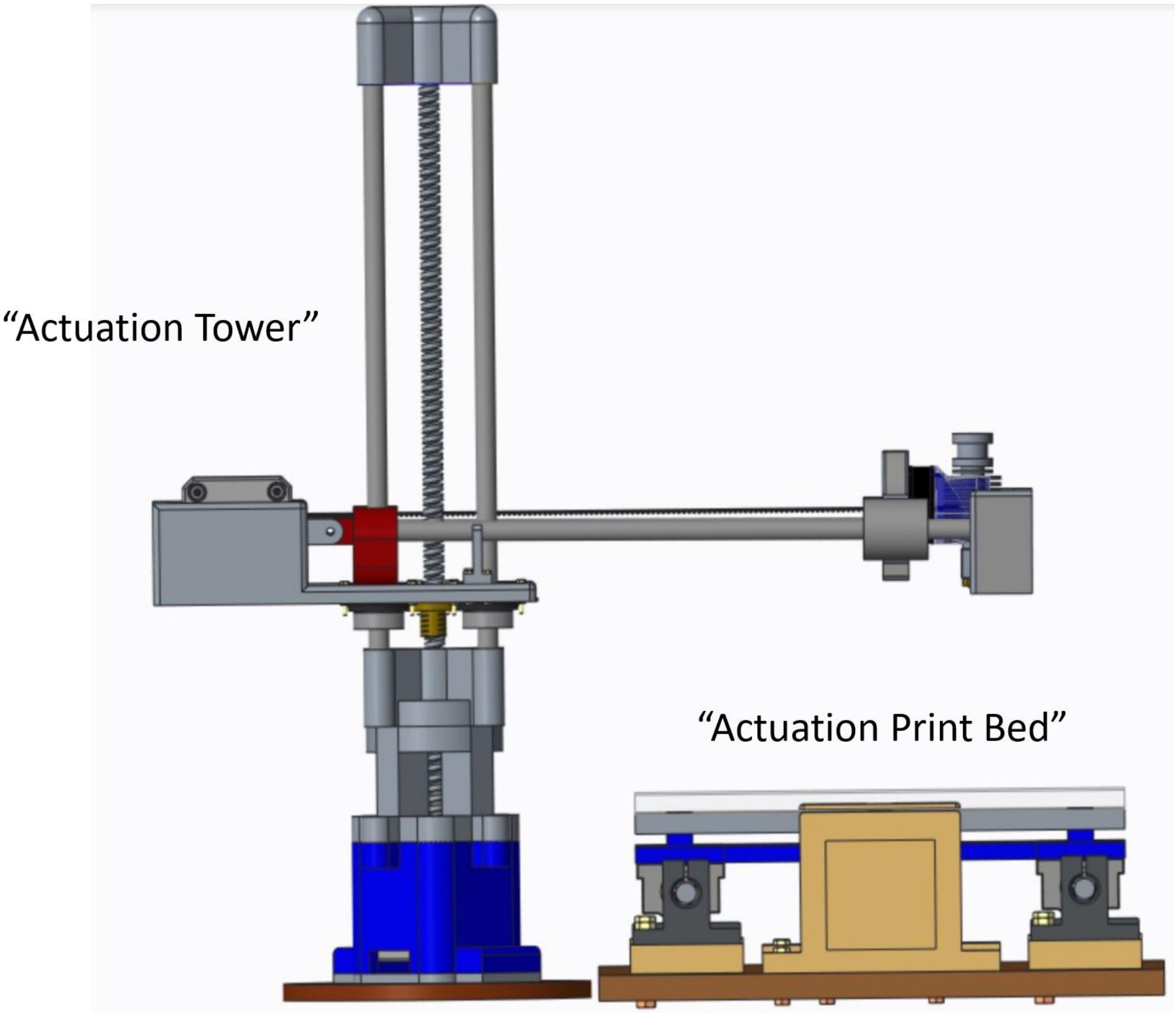


Figure 3.5: *Cylindrical Coordinate Space (Left) and Cartesian Coordinate Space (Right)*

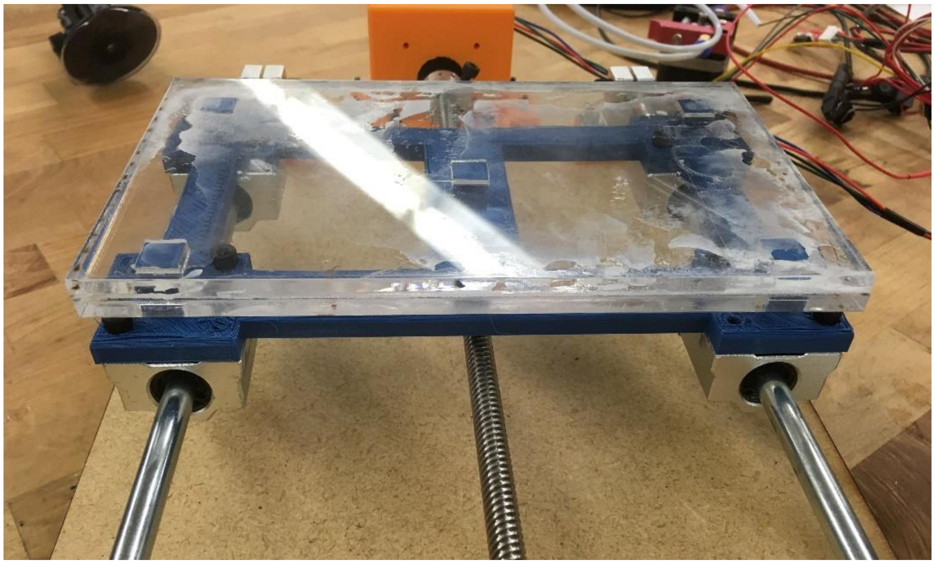


Figure 3.6: *Actuation Print Bed*

With the switch to the new Cartesian system, the printer's stability and as a result accuracy drastically improve. The new design still maintains a small portable profile as the print bed actuation unit is a rectangular body appropriate for a rectangular briefcase. Along with the physical benefits, from a software development standpoint, the new design allows for more accessible and available open source code to be applied and modified to our system. This significantly helps in the process of testing and calibration.

A2: Change to Belt Actuation Mechanism

The horizontal actuation unit saw massive improvements from the previous prototype, which used lead screw actuation to drive the extruder in linear translational motions with steel rods as a guide rails. This highly contributed to the weight of the horizontal section, which was not ideal both towards the overall design parameter of minimizing weight as well as contributing to deflections, moments, and other mechanical discrepancies that caused inaccuracies in printing.

Therefore, in order to reduce the weight in horizontal actuation, we changed the lead screw mechanism that drives the extruder in linear actuation with a belt driving system **(Fig. A7)**.

This design choice was justified as it reduced the weight from 3.2 pounds to 2.2 pounds while still maintaining an accuracy of ±0.01mm. Along with the belt, the guide rail material was changed from steel to a lighter aluminum material. The shafts were custom manufactured to design specifications from stock aluminum in the machine shop.

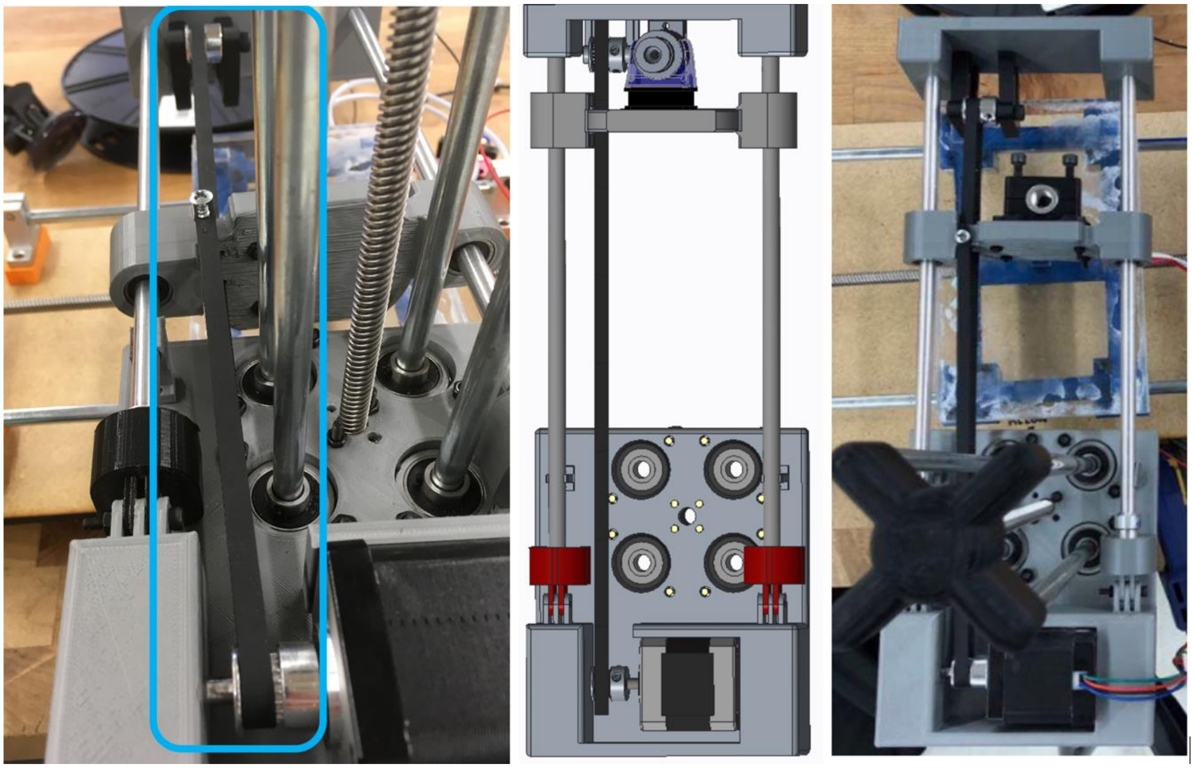


Figure A7: *Horizontal Actuation Unit with Newly Implemented Belt System*

The belt mechanism uses a GT2 belt and two pulleys, one is attached to the shaft of stepper motor, and the other is attached at the end of the horizontal actuation unit. Along with the belt system, two linear bearings are attached to the 3D printed extruder holder for smooth linear motion that guided by two aluminum rods.

A3: Change of Base Plate Design

For the base plate, our team decided to replace the machined plate to a 3D printed plate **(Fig. A8)**. The benefits of the 3D printed plate were that it is lightweight and that all of the necessary features, such as motor holder and folding and locking mechanism, could be directly designed into the base plate as one single part. This part experiences a lot of loads and stresses with all the components that connect to it. Thus, it was necessary to make the density (infill) of this part very high at 75%.

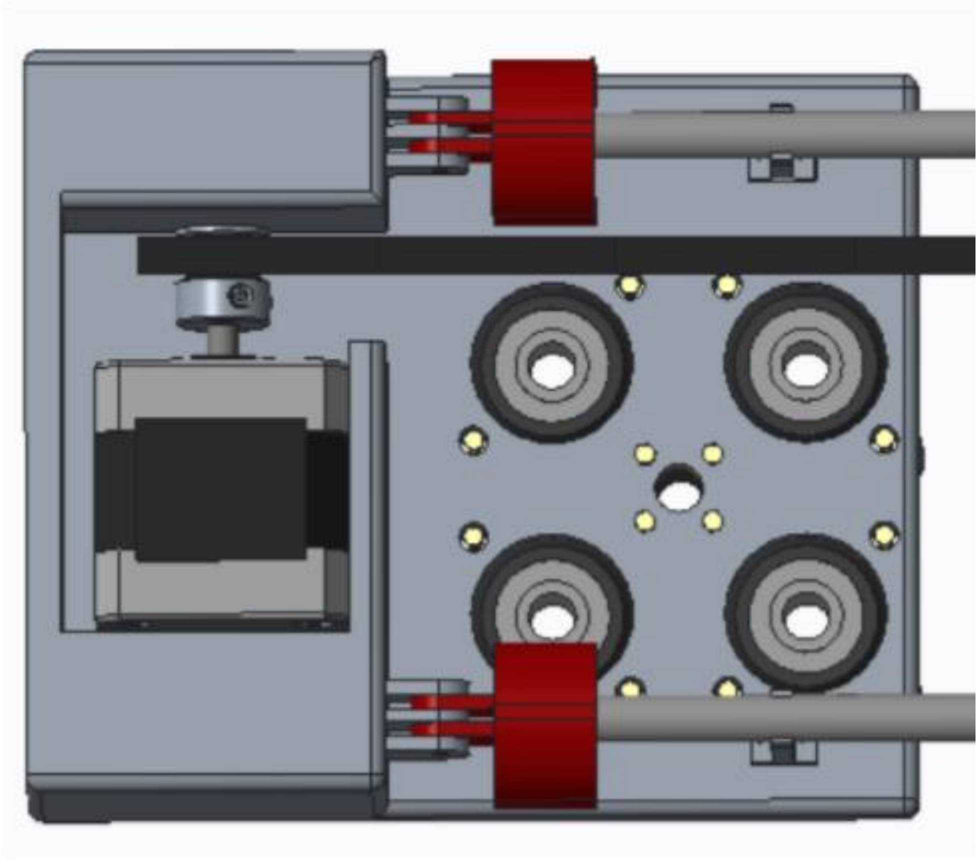


Figure A8: *Redesigned Base Plate with Built-in Motor Housing, Folding Mechanism, and Holes for Bearings*

A4: Improvements Toward Frictionless Actuation

To achieve a more frictionless actuation from the previous design, linear bearings were implemented for all actuation units. The linear bearings also helped with stability by mitigating any wobbling motions thanks to a tight fit with just enough tolerance for the rolling of the bearing against the shaft. In the vertical section, four linear bearings were attached to the base plate via screws for each of the four vertical guide rail shafts. Similarly for the print bed actuation unit, four linear bearings were also attached to the print bed via screws for smooth frictionless actuation in the y-direction. The x-axis actuator that held the extruder had two linear bearings implemented with press fit.

A traveler nut **(Fig. A9)** was also implemented to each of the lead screws to maximize smooth actuation. The traveler nut is machined to perfectly fit the corresponding threaded shaft while also providing more threaded area and support. It also helped to keep track of the increments of the length travelled per rotation, impacting the precision of the 3D printer.

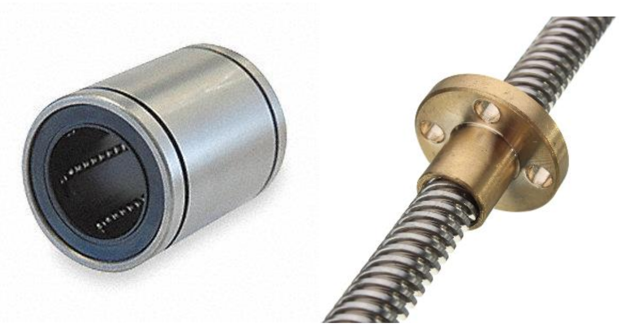


Figure A9: *Linear Bearing (left) and Traveler Nut (right)*

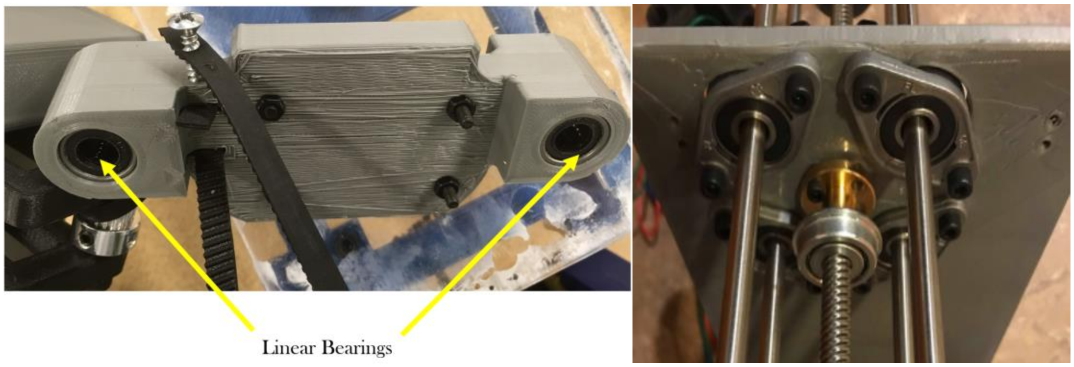


Figure A10: *Linear Bearings Implemented to New Design*

A5: Redesign of Folding and Locking Mechanism

We initially utilized hinge and toggle clamps to implement locking and folding mechanisms. The problems that we encountered using these components are rigidity and complicity, which is contrary to our goal of creating a minimalistic device. For that reason, we switched to a simpler design inspired by the existing locking mechanism in GoPro mount **(Fig. A12)**. Instead of using two different components, we only use one that is able to perform both functions. As shown in the pictures, the red components are responsible for both folding and locking.

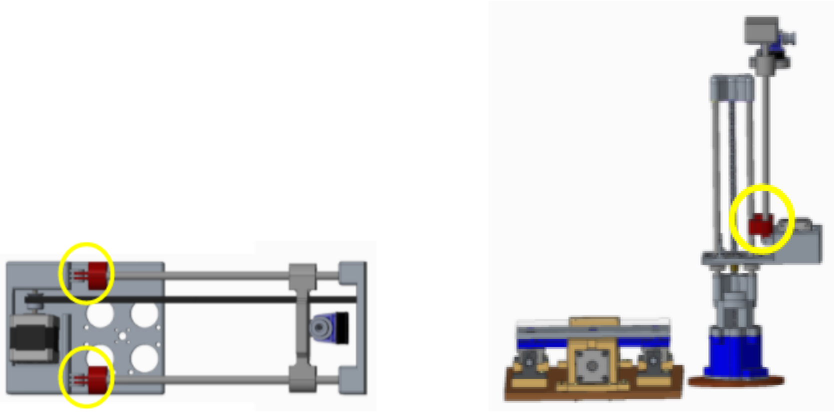


Figure A11: *CAD of Location of Folding and Locking Mechanisms*

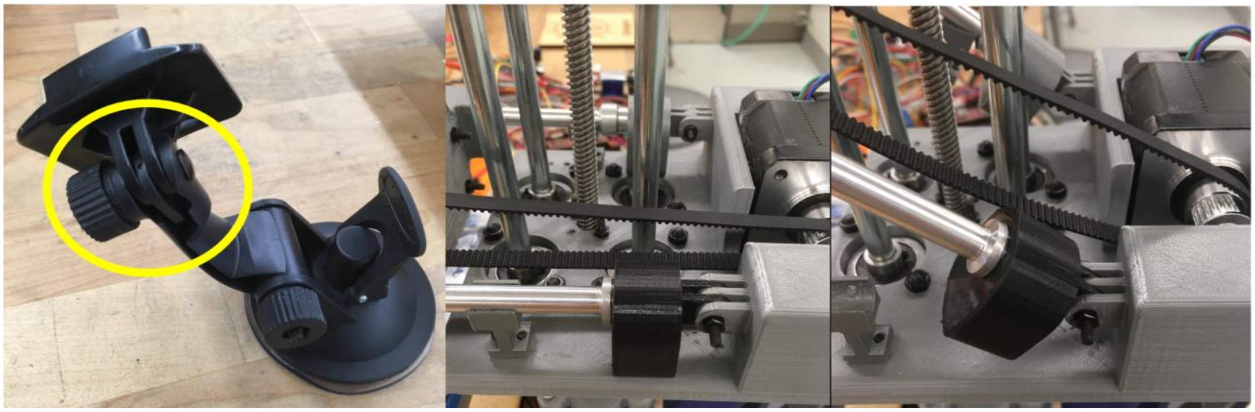


Figure A12: *GoPro Mount (Left) and Implementation of Mechanism to 3D Printer (Middle & Right)*

A6: Modifications to Vertical Section

From the previous DC 3, the linear motion in the vertical section was unsteady and it is not firm enough to support the weight from the horizontal section due to the difference in size. Therefore, to improve the rigidity of the vertical actuation component, we decided to widen the size of the vertical component by increasing the spacing between the rods to be able to have a more stable design. The previous design had the rods equally aligned on a circle of circumference 2 inches, whereas the new design had the rods aligned on circle of circumference 2.5 inches **(Fig. A13)**.

We also decided to use the standard rod and shaft size of 5/16” diameter that is used in most 3D printer. We also decided to use thicker and stronger shaft which is steel instead of aluminum.

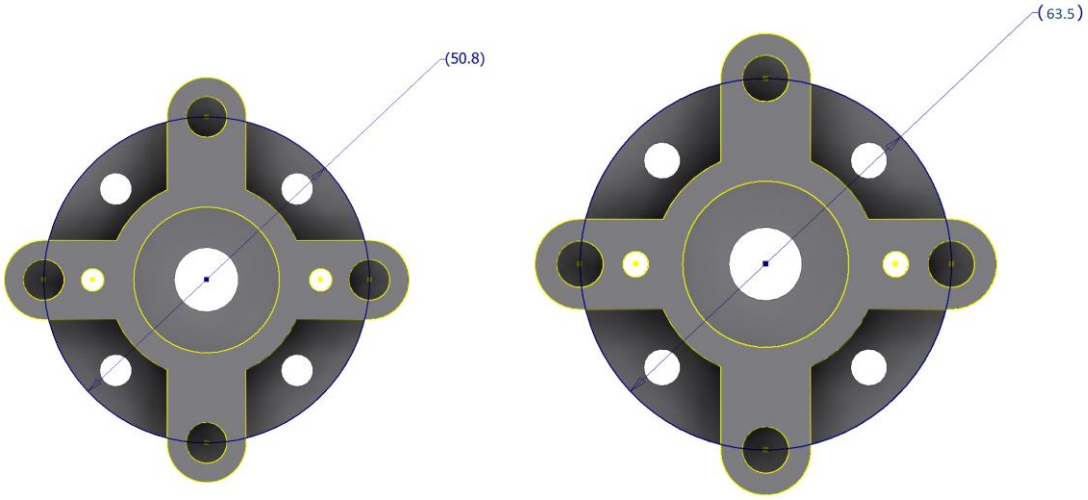


Figure A13: *Widening of the Vertical Section*

B. Electrical

B1: Updated Circuitry

In **Fig. B1** below shows the circuit for Solargami printer. We used 4 Nema 17 stepper motors, one E3D v6 hot end, a cooling fan, and 3 end stop switches. We also used one RAMPS 1.4a, an Arduino shield that is capable to control up to 5 stepper motors with 1/16 stepping precisions, power up all the electric components and also can control up to 3 thermistors for temperature measurement.

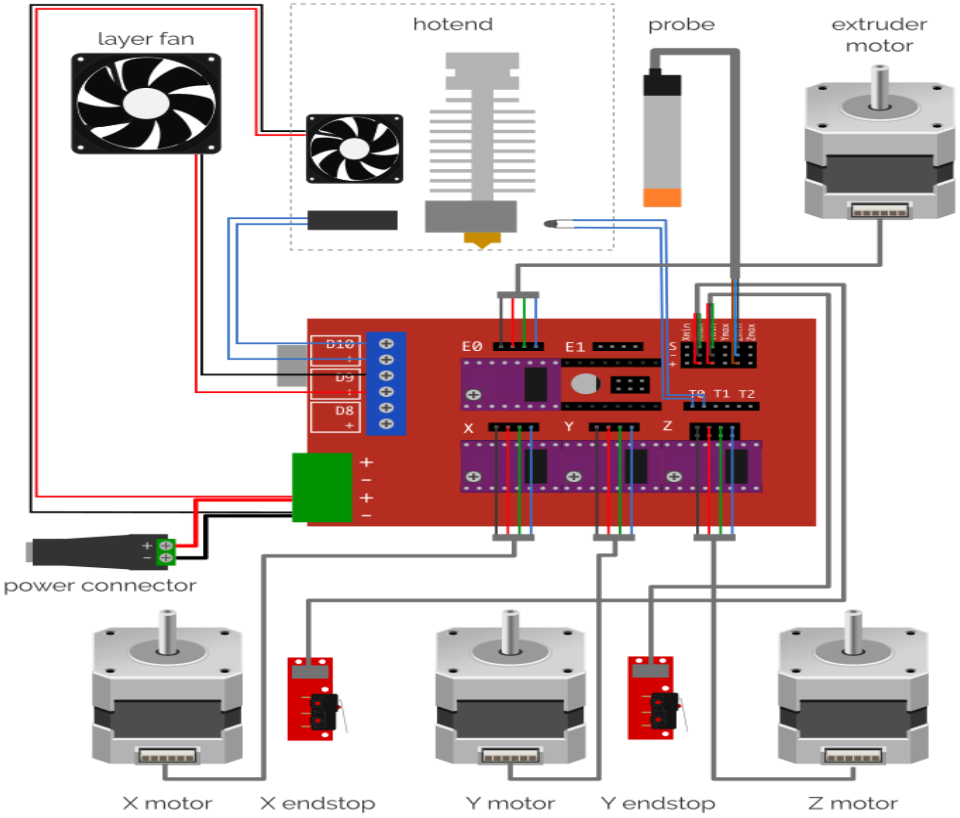


Figure B1: *Circuit Diagram and Electronics Breakdown*

B2: Solar Panel and Battery Selection

We will use 3X 40W portable solar panel and a 420Wh Marine deep battery for our solar system. It will take about 4 hours to completely charge this battery using the panel and also this battery can provide up to 10 hours printing for Solargami 3D printer.

Figure B2: *Coolis Foldable Solar Panels*

Figure B3: *Marine Deep Cycle Battery*

C. Software

Softwares that are used in this project are:

1) Arduino
2) Marlin*
3) Cura Engine

*Marlin is an open source firmware that can handle all the real time printing activities. Marlin is written in C++ and composed of many files, however, to use Marlin, we only need to edit and replace some line of codes in Configuration.h file. (https://github.com/MarlinFirmware/Marlin)

The following is the code that is edited in the Configuration.h file for our printer:

Baud Rate

```
#define BAUDRATE 115200
```

Baud rate is serial communication speed of the printer. This speed should be fast to avoid generating errors. We define baud rate 115200 because in most cases this speed gives a good balance between speed and stability.

Motherboard

```
#define MOTHERBOARD BOARD_RAMPS_14_EFB
```

Defining motherboard is most important setting in Marlin. Marlin need to know what board it will be running. In this case, we set the motherboard BOARD_RAMPS_14_EFB which is Ramps 1.4a. By setting the right board, Marlin can assign the right functions to all pins. If we not set this setting correctly, Marlin cannot take advantage of the full capabilities of the board and will lead to unpredictable results.

Extruders

```
#define EXTRUDERS 1
```

Since we only using one extruder, we defined EXTRUDERS 1 as shown on code above

Endstop Inverting

```
#define X_MIN_ENDSTOP_INVERTING true
#define Y_MIN_ENDSTOP_INVERTING true
#define Z_MIN_ENDSTOP_INVERTING true
```

These pieces of code above are to enable end stop switches in our printer. End stop switch is a mechanical switch that can trigger the printer to stop when an axis reaches its end of its motion.

Default Steps per mm

```
#define DEFAULT_AXIS_STEPS_PER_UNIT   {400, 80, 400, 500 }
```

Defining these setting correctly also very crucial to our printer as they determine how accurately the steppers will position the axes. Here we are telling the firmware that for moving x, y, z axis and extruder feeder, we need 400, 80, 400 and 500 steps respectively to produce a single millimeter.

SD Card

```
#define SDSUPPORT // Enable SD Card Support in Hardware Console
```

To enable SD card, we just need to define SDSUPPORT in the firmware.

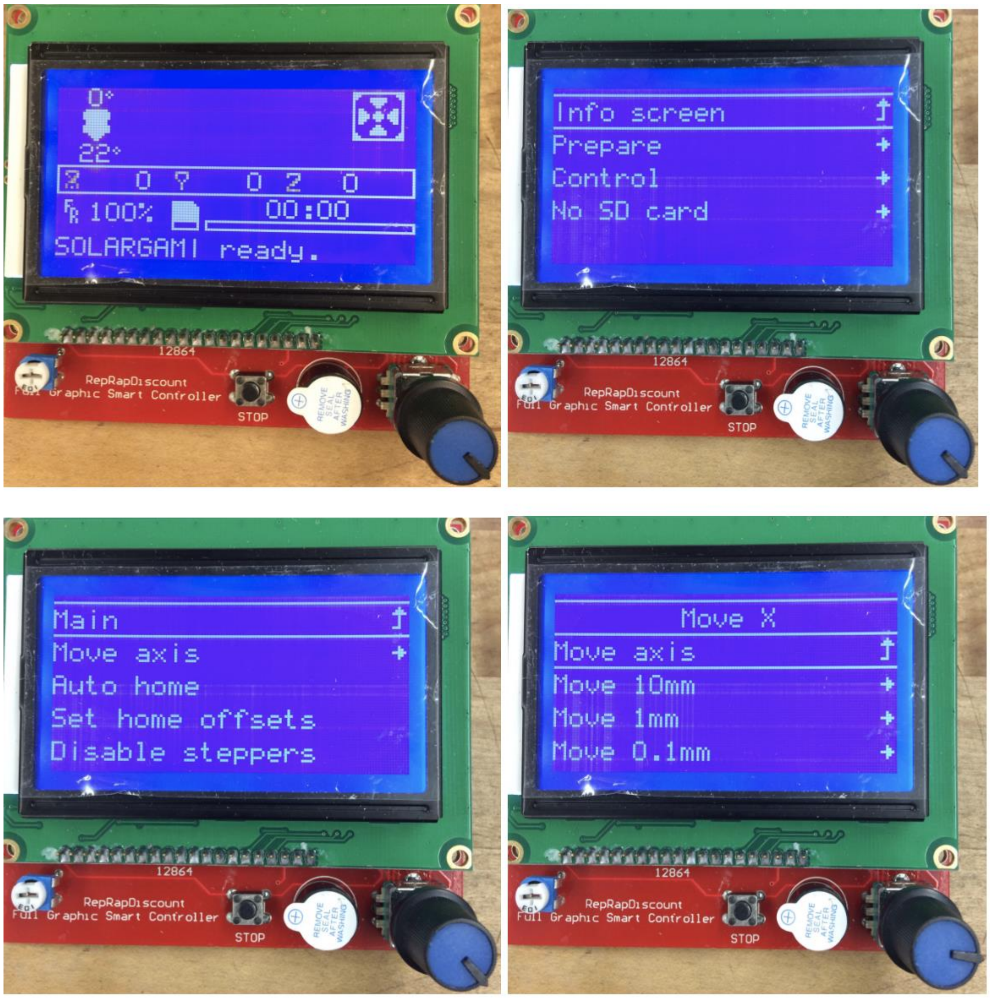
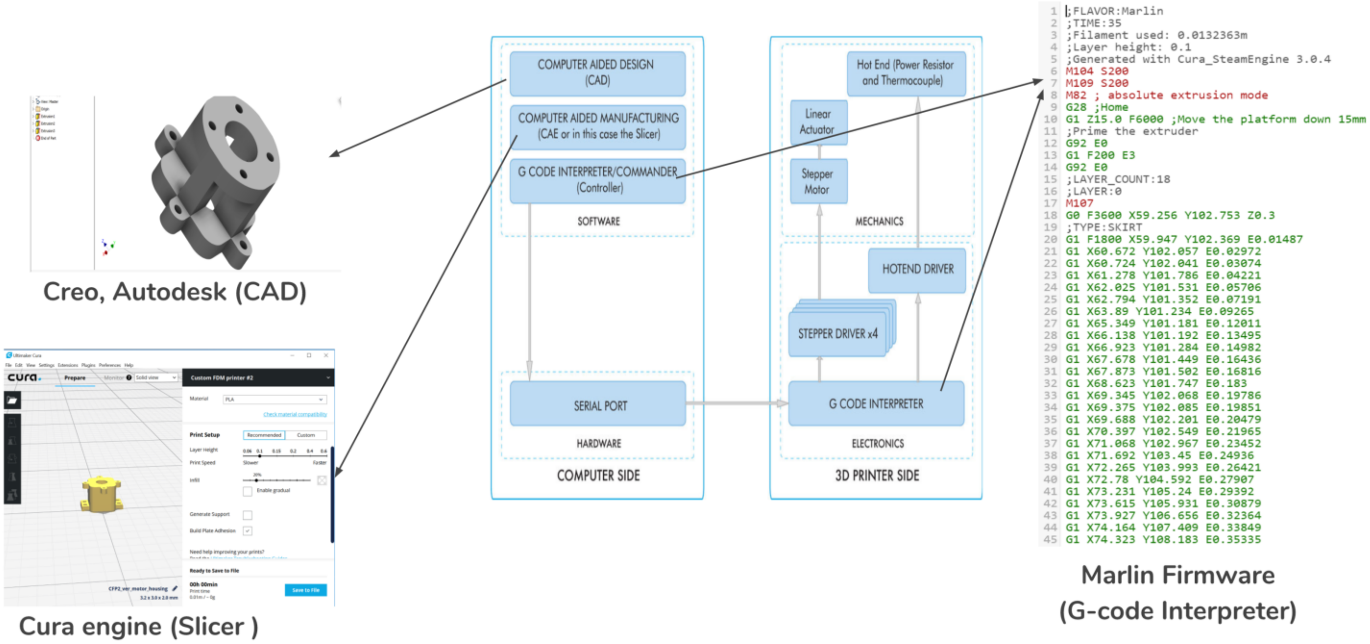


Figure C1: *UI LCD Controller*

Fig. C1 shows Marlin user interface that can be controlled using the rotating knob on the graphical LCD controller. There are a lot of features that we can use from this interface. One of them is auto home. Auto home is to positioned the printer to be at coordinate (0, 0, 0). We also can move each axis as shown in the Figure without connecting the printer to the computer. Other features are set the nozzle temperature, printing from SD card, set fan speed, Preheat PLA, set the PID values and etc.



```
;FLAVOR:Marlin
;TIME:35
;Filament used: 0.0132363m
;Layer height: 0.1
;Generated with Cura_SteamEngine 3.0.4
M104 S200
M109 S200
M82 ; absolute extrusion mode
G28 ;Home
G1 Z15.0 F6000 ;Move the platform down 15mm
;Prime the extruder
G92 E0
G1 F200 E3
G92 E0
;LAYER_COUNT:18
;LAYER:0
M107
G0 F3600 X59.256 Y102.753 Z0.3
;TYPE:SKIRT
G1 F1800 X59.947 Y102.369 E0.01487
G1 X60.672 Y102.057 E0.02972
G1 X60.724 Y102.041 E0.03074
G1 X61.278 Y101.786 E0.04221
G1 X62.025 Y101.531 E0.05706
G1 X62.794 Y101.352 E0.07191
G1 X63.89 Y101.234 E0.09265
G1 X65.349 Y101.181 E0.12011
G1 X66.138 Y101.192 E0.13495
G1 X66.923 Y101.284 E0.14982
G1 X67.678 Y101.449 E0.16436
G1 X67.873 Y101.502 E0.16816
G1 X68.623 Y101.747 E0.183
G1 X69.345 Y102.068 E0.19786
G1 X69.375 Y102.085 E0.19851
G1 X69.688 Y102.201 E0.20479
G1 X70.397 Y102.549 E0.21965
G1 X71.068 Y102.967 E0.23452
G1 X71.692 Y103.45 E0.24936
G1 X72.265 Y103.993 E0.26421
G1 X72.78 Y104.592 E0.27907
G1 X73.231 Y105.24 E0.29392
G1 X73.615 Y105.931 E0.30879
G1 X73.927 Y106.656 E0.32364
G1 X74.164 Y107.409 E0.33849
G1 X74.323 Y108.183 E0.35335
```

Figure C2: *Software System Anatomy and Relational Ecosystem*

Fig. C2 above shows the flow diagram from creating the 3D model to printing the final product. To create the 3D model or CAD, we used autoCad (diagram above) and Pro Engineer/CREO. Then, this model need to be saved in stereolithography format (.stl) for slicing.

Next, we used Cura Engine as our slicing software. Cura can slice the .stl file into several layers and output G-code for each layer. Then, we can save this G-file code into SD card or we can print directly using Cura via USB.

From here, Marlin will do its best to interpret the G-code and print the final product.

Section IV: Testing and Analysis

Extruder Testing

The E3D V6 Hot End is tested to ensure that the PLA can be melted smoothly for printing 3D product. Before testing the extruder, the first thing that is need to be done is to configure the temperature sensor. In Marlin, there are a lot of temperature sensors that were predefined by numbers. To ensure the thermistor works, some lines of codes in the thermal setting section in the configuration.h file was edited. We coded **#define TEMP_SENSOR_0 5** since we are using ATC Semitec 104-GT2 thermistor.

Next, for safety reasons, we coded **#define HEATER_0_MINTEMP 5.** This parameter will help to detect bad wiring. If any sensor goes below the minimum temperature set here, which is 5 degree Celsius, Marlin will shut down the printer with a "MINTEMP" error. Next, to prevent the printer from overloading and catching fire, we set the maximum temperature of the extruder to 230 degree Celsius with this parameter **#define HEATER_0_MAXTEMP 230.** If Marlin reads the temperature of the extruder above that value, it will immediately shut down the printer to avoid damages.

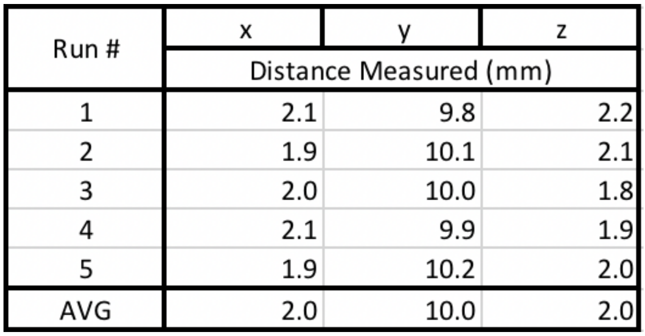
X-, Y-, and Z-Axis Calibration

By default, Marlin firmware has already a standard calibration installed for the axis resolution. However, since Solargami printer used threaded rod and belt, these standard values will not be appropriate or precise. To tell the firmware the step per millimeter (steps/mm) that our machine actually requires, some calibrations were done. By doing this calibration, we make sure that the distances in the g-code actually corresponds to the movement of the machine.

The default steps/mm for x, y and z axis from the firmware were 800, 800 and 4000 steps/mm respectively. To calibrate the machine, we instruct the stepper motor to move an axis a certain defined distance and measure the actual displacement. For instance, we tell x-axis to move 10mm and measured the displacement the carriage has travelled. Then, we can get the new steps/mm by using this formula:

$$\frac{New\ steps/mm}{Default\ steps/mm} = \frac{Input\ Distance\ (mm)}{Distance\ Measured\ (mm)}$$

Table below shows distance measured data for all axis for 10 mm input distance by using default Marlin steps/mm. This procedure was repeated, recompiled to the firmware for 5 times to get precise results. Then, by using the formula above, we can calculate the actual steps/mm for our printer.



Run #	x	y	z
	Distance Measured (mm)		
1	2.1	9.8	2.2
2	1.9	10.1	2.1
3	2.0	10.0	1.8
4	2.1	9.9	1.9
5	1.9	10.2	2.0
AVG	2.0	10.0	2.0

Sample calculations are shown to demonstrate the calibration protocol:

1. ***x*-axis calibration (horizontal actuation belt)**

   with input distance = 10mm and the average measured distance = 10mm.

$$\frac{New\ steps}{mm} = \frac{\left(\frac{80steps}{mm}\right)(10mm)}{10mm} = 80\ steps/mm$$

2. ***y*-axis calibration (lead screw for print bed)**

   with input distance = 10mm and the average measured distance = 2mm.

$$\frac{New\ steps}{mm} = \frac{\left(\frac{80steps}{mm}\right)(10mm)}{2mm} = 400\ steps/mm$$

3. ***z*-axis calibration (lead screw for vertical section)**

with input distance = 10mm and the average measured distance = 2mm.

$$\frac{New\ steps}{mm} = \frac{\left(\frac{80 steps}{mm}\right)(10mm)}{2mm} = 400\ steps/mm$$

The new steps/mm for x, y and z were measured to be 80, 400, 400 steps/mm respectively.

Electronics Power Usage

On idle

Solargami 3D printer used 1.183W of power on idle mode. The power usage on idle is very low which is good to save battery life when not in printing process.

Stepper Motor Holding Torque

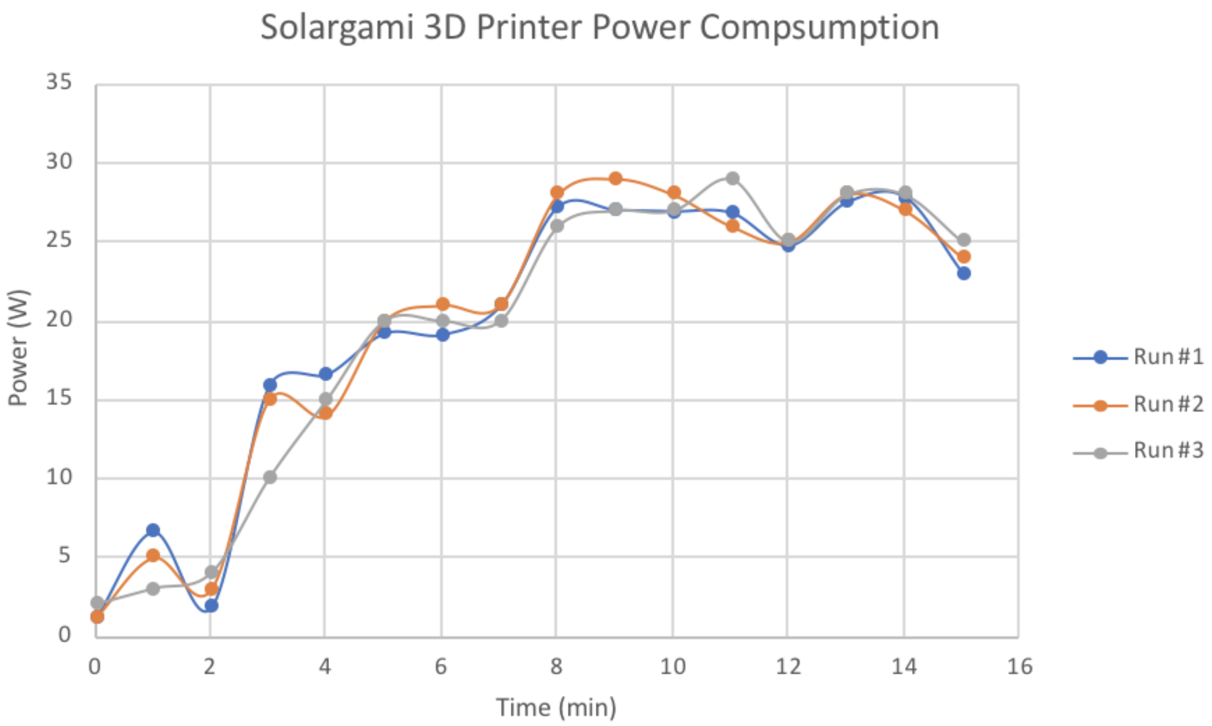
To maintain the holding torque, stepper motors consume a bit of power. Holding torque is what resists anything that might be trying to turn its shaft. After first turning on the printer, all stepper motors are off. To measure the holding torque, all the motor are turning on by homing the printer. The total power measured after homing was 6.643W. Subtracting this value with idle power usage yield 5.46W of power used for holding the motor.

Cooling Fan

Cooling Fan is crucial for good overhang performance on a PLA **3D printed** product. The power usage that was measured to run the cooling fan is about 0.697W.

Overall Print Power Usage

The overall print power consumption is shown in Figure below. This data was collected by printing a small 10x10x10mm cube.



The figure above shows the overall power usage for printing small cube. After min 2, the power spiking when the hot end comes on. Then the power usage fluctuates depending on the electronics used during the printing process. The highest power recorded is 29W, minimum is 1.183W and the average is 23.29W.

Upcoming Testing Cycles To Be Done

Appropriate calibration in the x,y, and z axis, and leveling the print bed are very important as these determine the printing quality of the printed products. Printing accurate models are really vital especially printing the medical modeling. The 4 stepper motors; X-axis motor, Y-axis motor, Z-axis motor, and extrusion motor must be calibrated appropriately. This must be done in the printing software configuration that controls the mechanical output using G-codes as the language for the printing software to communicate with the printer.

1: Print bed (leveling & adhesion)

We are going to perform simple test by using a piece of paper with average thickness of 70 microns. The first step is to heat up the nozzle and slowly move the hotend to the center of the bed. Once the nozzle starts to grab on the paper, the endstop will be set. The nozzle now will be moved over to the first corner of the bed and a paper will also be used. This time, instead of the endstop, the height of the bed's corner will be adjusted. In the test, we anticipate the print bed to be poorly leveled and since we do not utilize screw mechanism at the corners, bed adjustments would be quite challenging. The to-and-fro motion of the print bed will also affect its levelness. So, after every complete motion, we will test its offset. For the upcoming cycle, modification on print bed will be implemented so that leveling can be done more efficiently, as failure to do so will result in very poor print quality.

For our first prints, we will expect warping. Warping typically occurs when the print does not adhere well to the print bed which means that adhesion of the print bed is not sufficient. We are going to perform the warping test by experimenting surfaces with different amount of adhesion. This might not seem as a significant issue, but excessive warping and curling will invalidate the models' function.

2: Vertical Actuation

Testing on the smoothness of the vertical actuation during the upwards and downwards motion for accuracy:

We tested the upwards and downwards motion of the vertical actuation system by having the linear bearings and traveller nut on all shaft and rods. We made a test on the motor rotation with the elevation of the printed plate. The elevation of length travelled per rotation is recorded to calibrate the vertical actuation. Comparing to the previous design, we managed to significantly increase the smoothness of our vertical actuation system which also helps improve the accuracy of the printing processes. For the upcoming modification on vertical system, we are determined to improve more on the accuracy that it delivers after receiving the command from Arduino.

3: Horizontal Actuation

The extruder is driven by the belt and the belt tension plays an important part in producing good models. To test its tension, the rule of thumb is that the belt should deflect by 1/64 inch per inch of length. A ruler will be positioned upright when the print head in its home position to measure the height of the belt in its resting state. The belt is slightly deflected with the hand. If the belt moves more than ¼ inch then it means that it is loose and will affect print quality. To tackle this, the belt will be replaced with a shorter one, and repeat the test.

4: Extrusion Motor

Testing on the smoothness of the motor to drive PLA filament into the extruder for printing process:

We first calibrate the motor to be able to feed the PLA filament continuously during the printing process. The calibration of the extrusion motor is checked by heating up the extruder to the recommended temperature for the filament. Tape is used to mark a few cm up the filament and then measured the distance from the tape to the entrance into the extruder. The printer is then told to extrude 10 mm of the filament and it is measured again to check the accuracy. Rate of extrusion also matters to be able to tell the accurate amount of material extruded per given time.

We still in the process of improving the accuracy of the extrusion motor to be able to extrude proper amount of filament per given time and manage to feed the extruder continuously during printing process.

5: Vibrations Testing

A combination of Finite Element Analysis via ANSYS Workbench and mechanical instrumentation, particularly a chain series of accelerometers will be used to monitor stability and the presence of vibrations along different sectional components of the device. An output frequency and amplitude from the accelerometer data will help characterize the intensity of vibrations within the system. By mapping the response, refinements and modifications can be made to the mechanical structure to mitigate vibrations that will effect print quality.

Testing protocol would follow first the syncing of all accelerometers to a data acquisition module. Then a series of predetermined standard movements in a print such as combinational translational motions would be repeated and data will be recorded and analyzed.

Section V: Bill of Materials

	Prototype 4			
No of Item	***Material***	***Quantity***	**Total Cost**	**Supplier**
1	*Stepper Motor*	*3*	$32	Ebay
2	*Stepper Motor Driver (includes a microcontroller)*	*3*	$44.57	Ebay
6	*Aluminum Timing Pulley and Belt*	*1*	$8.99	Amazon
7	*Linear Bearing Ball Bushing*	*6*	$7.40	Amazon
8	*Filament Feeder*	*1*	$27.98	Amazon
9	*Block Bearings and Lead Screw*	*4*	$25.14	Octagon Star
10	*Flange-Mount Ball*	*3*	$27.37	McMaster-Carr
11	*E3D V6 Hot End*	*1*	$18.99	Amazon
12	*2 8mm Dia. Steel Rods and a Lead Screw*	*1*	$11.89	Hillsboro Hardware
13	*Lead Screw and Copper Travelling Nut*	*1*	$11.99	Amazon
	Total Cost	***$216.32***		

Section VI: Budget

Prototype 1	Activites	Cost per Hour	Labor Hours	# of Engineer	Total Cost ($)
	CAD Modeling	-	5	4	-
	Machining	-	2	1	-
	Laser-cutting	-	1	1	-
	Fabrication	-	8	5	-
	Electronic Assembly	-	-	-	-
Prototype 2	**Activites**	**Cost per Hour**	**Labor Hours**	**# of Engineer**	**Total Cost ($)**
	CAD Modeling	-	4	2	-
	Machining	-	2	1	-
	Laser-cutting	-	1	1	-
	Fabrication	-	5	5	-
	Electronic Assembly	-	3	2	-
Prototype 3	**Activites**	**Cost per Hour**	**Labor Hours**	**# of Engineer**	**Total Cost ($)**
	CAD Modeling	-	5	2	-
	Machining	-	4	1	-
	Laser-cutting	-	1	1	-
	Fabrication	-	9	5	-
	Electronic Assembly	-	5	1	-
Prototype 4	**Activites**	**Cost per Hour**	**Labor Hours**	**# of Engineer**	**Total Cost ($)**
	CAD Modeling	-	15	4	-
	Machining	-	10	2	-
	Laser-cutting	-	3	2	-
	Fabrication	-	20	5	-
	Electronic Assembly	-	10	1	-

Prototype 1

No.	Design	Material	Source	Cost
1	Assembly Line Robot Arm Design	MDF Board (laser-cut)	Design Council	-
2	Folding Arch Design	Aluminum Extrusion 20 mm x 20mm	Design Council	-
3	Modified Elevator Design	MDF Board (laser-cut)	Design Council	-
4	Folding Box Design	MDF Board (laser-cut)	Design Council	-
Total Cost				**$0**

Prototype 2

No.	Material	Source	Quantity	Total Cost
1	25cm Long Threaded Shaft 6.25mm Diameter	Design Council	-	-
2	Toggle Latch Clamp	Amazon	5	$12.55
3	Planetary Gear (Acrylic - laser cut)	Design Council	-	-
4	Stainless Steel Door Hinge	Design Council	-	-
5	3D Printed Motor Holder	Design Council	1	-
6	3D Printed Shaft Coupler	Design Council	1	-
7	Rectangular Metal Piece	Machine Shop	1	-
Total Cost				**$12.55**

Prototype 3

No.	Material	Source	Quantity	Total Cost

1	25cm Long Threaded Shaft 6.25mm Diameter	Design Council	2	-
2	Toggle Latch Clamp	Amazon	5	-
3	Pastic Bevel Gear	Mc-master carr	2	$16.65
4	Stainless Steel Door Hinge	Design Council	2	-
5	E3D V6 Hot End	Amazon	1	$17.49
6	3D Printed Motor Holder	Design Council	2	-
7	3D Printed Shaft Holder	Design Council	4	-
8	3D Printed Motor + Bevel Gear Holder	Design Council	1	-
9	1.4 Ramp, Arduino Mega and LCD Smart Controller	Ebay	1	$44.57
10	Nema 17 Stepper Motor 2.0A 59N.cm	Amazon	1	$32.00
11	Rectangular Metal Piece	Machine Shop	1	
Total Cost				**$110.71**

Prototype 4				
No.	**Material**	**Source**	**Quantity**	**Total Cost**
1	30cm Long Threaded Shaft 8mm Diameter	Design Council	2	-
2	1ft Steel Rod 8mm Diameter	Hillsboro Hardware	2	$7.92
3	1ft Threaded Shaft 8mm Diameter	Hillsboro Hardware	1	$3.97
4	1.4 Ramp, Arduino Mega and LCD Smart Controller	Ebay	1	$44.57

5	Nema 17 Stepper Motor 2.0A 59N.cm	Amazon	1	$32.00
6	Nema 17 Stepper Motor Bipolar 4	Design Council	1	-
7	3D Printed Base Motor Holder	Design Council	1	-
8	3D Printed Vertical Motor Housing	Design Council	1	-
9	3D Printed Vertical Top Shaft Holder	Design Council	1	-
10	3D Printed Vertical Bottom Shaft Holder	Design Council	1	-
11	3D Printed Vertical Shaft Spacer	Design Council	1	-
12	Laser Cut Reference Board	Design Council	1	-
13	Mounted Pillow Block Linear Ball Bearing	Design Council	4	-
14	Filament Feeder	Amazon	1	$27.98
15	Linear Bearing Ball Bushing	Amazon	6	$7.40
16	E3D V6 Hot End	Amazon	1	-
17	E3D V6 Hot End	Amazon	1	$18.99
18	Flange-Mount Ball	Amazon	3	$27.37
19	SK8 Linear Rail Shaft Support	Design Council	4	-
20	30cm Steel Rod	Design Council	2	-
21	Laser Cut Print Bed (Acrylic)	Design Council	2	-
22	3D Printed Motor Case	Design Council	1	-
23	3D Printed End Case	Design Council	1	-
24	Aluminum Guide Rod	Design Council	2	-
25	3D Printed Shaft Locker	Design Council	2	-
26	Lead Screw and Travelling Nut	Amazon	1	$11.99
27	4 Block Bearings and Lead Screw	Amazon	1	$25.14
28	3D Printed Pulley Mount	Design Council	1	-

29	3D Printed Cover End	Design Council	1	-
30	2 Aluminum Timing Pulleys and GT2 Belt	Amazon	1	$8.99
31	3D Printed Shaft Holder	Design Council	2	-
32	3D Printed Extruder Mount	Design Council	1	-
33	3D Printed Plate	Design Council	1	-
Total Cost				**$216.32**

Overall Cost for Every Prototype

	Prototype 1	**Prototype 2**	**Prototype 3**	**Prototype 4**
Total Labor Cost	$0	$0	$0	$0
Material Cost	$0	$12.55	$110.71	$216.32
Overall Cost	**$0**	**$12.55**	**$110.71**	**$216.32**

Section VII: Conclusions and Final Plans

Design Cycle 4 has been an extremely successful term with significant amounts of progress made in both the mechanical and electrical aspects of the projects. Those two components are effectively solidified as the final design for Solargami as of now. Minor changes and modifications are to be expected as testing and calibration continues. However, no major changes are expected.

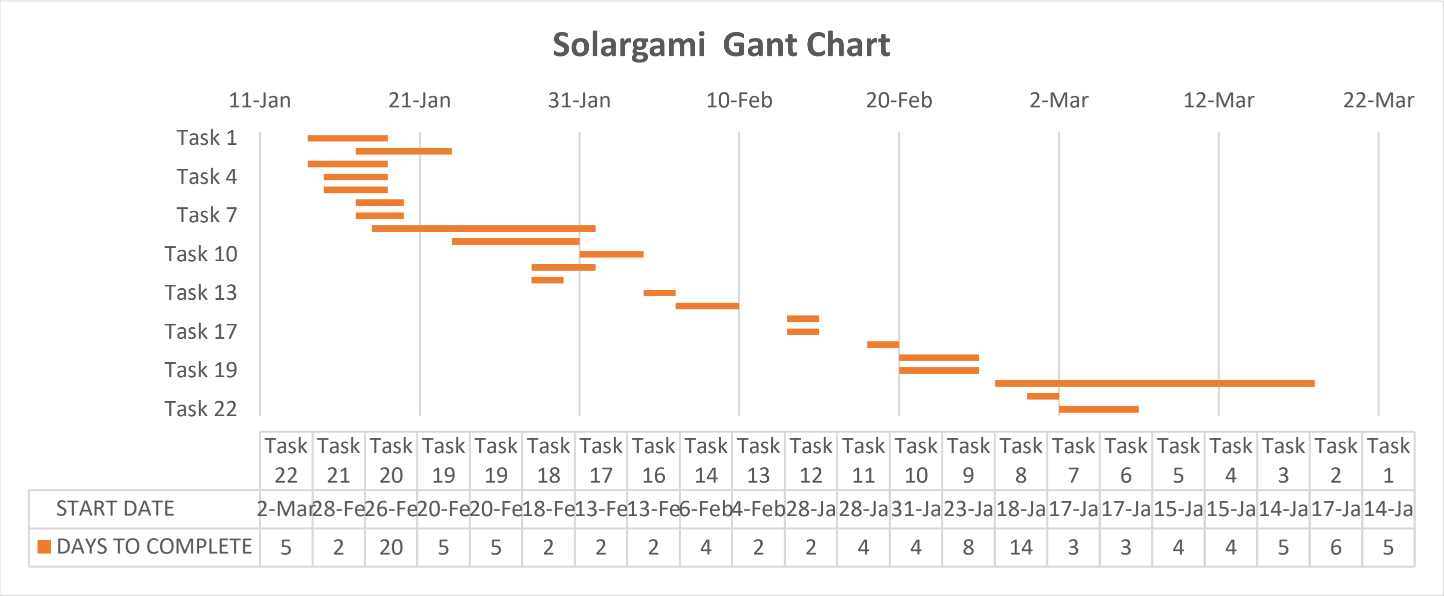
The biggest successes in this past design cycle included developing a better and more reliable folding/locking mechanism, drastically improving actuation methods via implementation of bearings, and shifting to a cartesian coordinate system configuration. All of these changes have immensely contributed to the larger goal of developing a more stable and accurate 3D printer, while maintaining a small collapsible profile and weighing only *9.53 pounds*.

With a now reliable and well-functioning mechanical structure in place, higher software integration and testing has begun. Basic prints such as cubes and cylinders have been printed for testing and calibration. This has helped begin the troubleshooting and refining phase of the project.

In the final phase of this project's journey, testing will be the central theme of focus. As emphasized throughout the lifecycle of this project, accuracy and resolution are extremely crucial factors for a successful 3D Printer. Therefore, with a newly developed 3D Printer such as Solargami, extensive and intensive testing and fine tuning will continue to be center of attention between now until Design Day.

In parallel with calibrating print resolution and accuracy, we will be the testing and implementing the rechargeable batteries and solar panels for powering the device. Although, this is a more auxiliary component of focus, the solar power aspect is still very much an important part of the overall innovation the Solargami has over current 3D printers.

Below is implementation plan for Solargami between now and Design Day (April 23, 2018):



	Task 22	Task 21	Task 20	Task 19	Task 19	Task 18	Task 17	Task 16	Task 14	Task 13	Task 12	Task 11	Task 10	Task 9	Task 8	Task 7	Task 6	Task 5	Task 4	Task 3	Task 2	Task 1
START DATE	2-Mar	28-Fe	26-Fe	20-Fe	20-Fe	18-Fe	13-Fe	13-Fe	6-Feb	4-Feb	28-Ja	28-Ja	31-Ja	23-Ja	18-Ja	17-Ja	17-Ja	15-Ja	15-Ja	14-Ja	17-Ja	14-Ja
■ DAYS TO COMPLETE	5	2	20	5	5	2	2	2	4	2	2	4	4	8	14	3	3	4	4	5	6	5

TASK	DESCRIPTION	START DATE
Task 1	Rebuild motor and bevel case with rotational plate	14-Jan
Task 2	Rebuild motor and coupler case	17-Jan
Task 3	Build holder for belt and pulley (horizontal parts)	14-Jan
Task 4	Purchase timing pulley and belt	15-Jan
Task 5	Purchase ball bearing bushing	15-Jan
Task 6	Test heating part of extruder	17-Jan
Task 7	Motor testing	17-Jan
Task 8	Figure or plan n solar power systems	18-Jan
Task 9	Fabricate new shafts and plates for verticle actuation	23-Jan
Task 10	Implement proper locking mechanism	31-Jan
Task 11	Purchase roller bearings and lead screw with travelling nut for vertical actuation	28-Jan
Task 12	Test vertical part (pulley and belt system)	28-Jan
Task 13	Test rotational and vertical motion	4-Feb
Task 14	Testing code for the printing process	6-Feb
Task 16	Calibrate the PLA motor	13-Feb
Task 17	Calibrate extruder motor	13-Feb
Task 18	Build the y-axis printbed (change from cylindrical to cartesian coordinate system)	18-Feb
Task 19	Calibrate x,y,z motor	20-Feb

Task 19	Re-calibrate all motors (x,y,z motor, PLA motor and extruder motor)	20-Feb
Task 20	Printed testing part (basic shape : small cube, triangular)	26-Feb
Task 21	Set the printbed and the printer align	28-Feb
Task 22	Figure how to put the printer in a suitcase	2-Mar