Next Generation 3D Printer

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1. Introduction

The engineering design program at Northern Arizona University (NAU) is striving to assist in the collaboration of its students with fellow organizations to help instill the necessary qualities and experience needed in future careers. As a realization of this ideal, the Novakinetics Team has been organized through a senior-level capstone course to work with their client, Novakinetics, to conceptualize and design a more efficient and cost effective 3D printer which could be utilized in the production of aerospace composite molds and tooling.

With regards to manufacturing, the 3D printing process has advantages as well as disadvantages. Novakinetics recognizes both the advantages and disadvantages of 3D printing and sees a potential to use these printers due to their high accuracy and precision. Due to the limitations of most 3D printers such as print speed, print volume, cost, and accuracy on cheaper machines; the development of a new design is necessary. A design that overcomes these disadvantages and limitations while maintaining product quality would greatly benefit companies such as Novakinetics. Such benefits include the reduction of labor, an increase in production speeds as well as decreased production cost.

Through state of the art research (SOTA) and a corresponding quality function deployment (QFD), the team has established the objectives to increase the print speed, maximize accuracy, reduce maintenance, make it safe to operate while easy to use, and be economical. With a design that can overcome such limitations, the team will be able to produce a finished product that will optimize Novakinetic's current manufacturing process. The following report will discuss the overall design process as well as the manufacturing process of the team's 3D Printer.

2. Problem Definition

2.1 Needs Statement

Novakinetics is dissatisfied with the current lead time for creating molds and tooling and requires a different approach to creating their products.

2.2 Project Goal

The goal of the project is to aid Novakinetics in optimizing their manufacturing process by utilizing a 3D printer.

2.3 Objectives

It is important to clearly outline the objectives by establishing a method of measurement for each objective as well as a corresponding unit of measurement. This allows us to quantitatively see how the final product meets each objective. The team's objectives are summarized in (**Table 2.1**).

Table 2.1- Project Objectives

Objective	Measurement	Units
Fast Print Speed	Filament / Time	mm/s
Accuracy	Length	mm
Maintenance	Time	Hours/Week
Safe to Operate	OSHA	Unitless
Ease of Use	Time to Proficiency	Hours
Economic	Cost	US Dollars

2.4 Constraints

There are two different types of constraints for this project. The first type is the constraints of current 3D printing methods. These constraints exist given the nature of 3D printing. The second is the constraints of the client. Novakinetics has provided the team with the requirements needed to accomplish their need statement. In order to achieve these requirements, the team listed the constraints as shown in (**Table 2.2**).

Table 2.2- Project Constraints

Constraints	Parameter
Part thickness	> 1.25mm
Surface dimension tolerance	±0.8mm
Resolution	< 0.5mm
Print volume	> 1m^3 (1m x 1m x 1m)
Power use	< 480V, 200A

Part thickness refers to the minimum length the part needs to be in order to print. This is a constraint that is very common on 3D printers. Surface dimension variance relates to the actual measurement of a print dimension in comparison to the desired dimensions. Resolution is thickness of each layer or the degree of detail in each layer. The part will appear more smooth and defined as the resolution dimension decreases. Print volume is the volume based upon the dimensions in the x, y and z direction. More print volume means larger parts can be created. Finally, power usage is the total power the final design will use. Low power usage is desired in manufacturing because the company will spend less money running the machine.

3. Quality Function Deployment (QFD)

3.1 Introduction

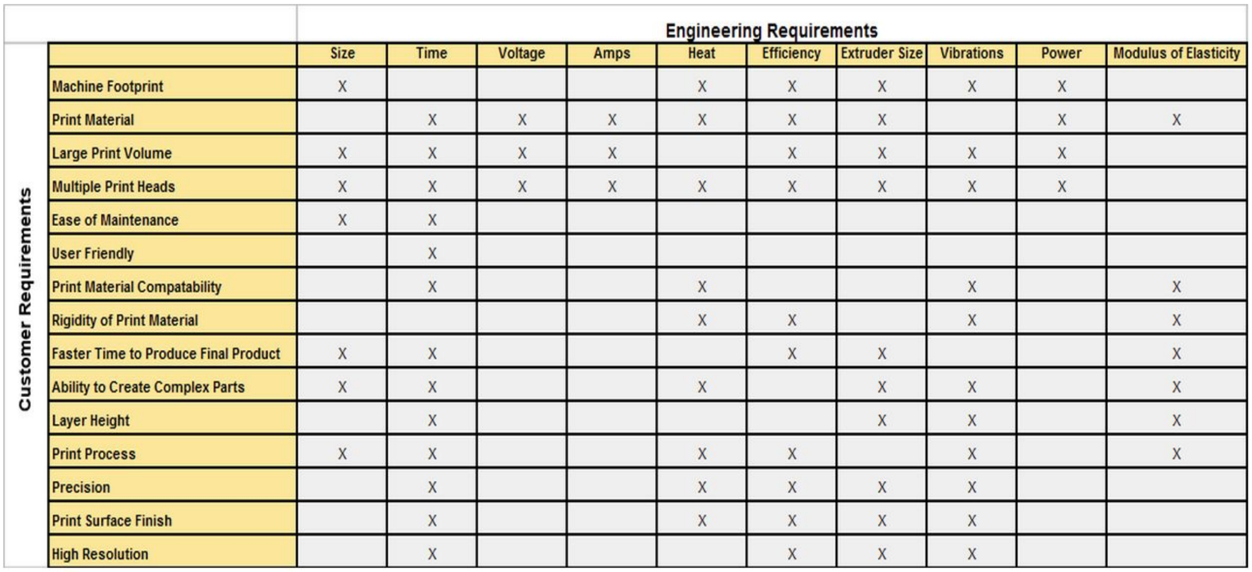
The following section discusses three important techniques for the problem definition. The Quality Function Deployment (QFD) is the first step to be taken after meeting the client. It establishes a starting point and sets up the rest of the project. After the QFD is established, the House of Quality can then be created in order to compare the engineering requirements formed from the QFD. Lastly, a project plan is formed in order to keep the team on track for the rest of the project. The following sections will discuss these three techniques in further detail and how they relate to this project.

3.2 QFD

After talking and meeting with Novakinetics, the team was able to ask important questions in regards to the project goals. The QFD as seen in (**Table 3.1**), was created after the first meeting with Novakinetics. The questions asked form the basis of where the team's customer requirements come from. Some of the customer requirements are having a large print volume, the use of multiple print heads, faster time to produce the final product, and the ability for the printer to create complex parts. Keeping these customer requirements in mind, the team then came up with engineering requirements. These are important to keep in mind when trying to achieve all of the customer requirements. Some of the engineering requirements include size of both the machine and parts, time, heat, efficiency, extruder size, and vibrations.

After these engineering requirements were established, they were then compared to the customer requirements. This is done in order to determine the most important engineering requirements for the particular set of customer requirements. By reference of the QFD in (**Table 3.1**), the X's are denoting a relationship between the customer requirements and the engineering requirements. The important engineering requirements are the ones that have the most amount of X's. For this project, it can be noted that the most important engineering requirements are time, efficiency, and vibrations. These engineering requirements are going to be the main ones the team will focus on when designing the new 3D printer. Now that the engineering requirements are established, a house of quality (HOQ) can be formed.

Table 3.1- QFD

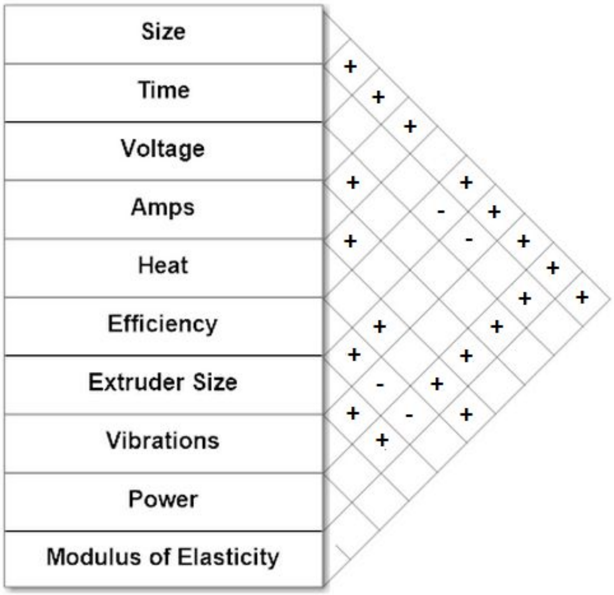


		Engineering Requirements									
		Size	Time	Voltage	Amps	Heat	Efficiency	Extruder Size	Vibrations	Power	Modulus of Elasticity
Customer Requirements	Machine Footprint	X				X	X	X	X	X	
	Print Material		X	X	X	X	X	X		X	X
	Large Print Volume	X	X	X	X		X	X	X	X	
	Multiple Print Heads	X	X	X	X	X	X	X	X	X	
	Ease of Maintenance	X	X								
	User Friendly		X								
	Print Material Compatability		X			X			X		X
	Rigidity of Print Material					X	X		X		X
	Faster Time to Produce Final Product	X	X				X	X			X
	Ability to Create Complex Parts	X	X			X		X	X		X
	Layer Height		X					X	X		X
	Print Process	X	X			X	X		X		X
	Precision		X			X	X	X	X		
	Print Surface Finish		X			X	X	X	X		
	High Resolution		X				X	X	X		

3.3 House of Quality (HOQ)

The HOQ is essential in understanding how each of the engineering requirements are related to each other. The HOQ is a visual way of representing both the positive and negative relationships. The HOQ can be seen in (**Table 3.2**). After reviewing the HOQ, it is important to note the positive relationships. An example of these include size and time. There is a positive relationship between the two because if the size of the parts being printed are scaled up, the time it takes to print it also goes up. An example of a negative relationship is between the extruder size and the time it takes to print a part. If the extruder is small, resolution will be better but this will greatly increase the time it takes to print a part. The house of quality is essential in determining these types of relationships. It will help the team in the design portion of this project by showing how different features in the design affect the final outcome. In order for the team to be successful and efficient a project plan was then created to keep the team on track.

Table 3.2- House of Quality



	Size	Time	Voltage	Amps	Heat	Efficiency	Extruder Size	Vibrations	Power	Modulus of Elasticity
Size		+	+	+		+	+	+	+	+
Time						-	-		+	
Voltage				+					+	
Amps					+				+	
Heat							+		+	+
Efficiency							+	-	-	
Extruder Size								+	+	
Vibrations										
Power										
Modulus of Elasticity										

4. Benchmarking

4.1 Introduction

To set benchmark performance expectations, it is important to research technology that is currently on the market. To begin the team's benchmarking process the team looked for 3D printers that utilize multiple extruders; however to the team's knowledge, there are currently no 3D printers that use multiple extruders on the market. Research was then focused on 3D printers with large print volumes near 1m^3. This led the team to the BigRep One and the Fortus 900mc, two very different design approaches to a large scale 3D printer.

4.2 State of The Art Research (SOTA)

The BigRep One, as seen in (**Figure 4.1**), is the first large scale 3D printer commercially available. It has a build volume of 1.1m^3 (1.1m x 1.0m x 1.0m) with a resolution and positional accuracy of 100 microns. It is also one of the cheapest large scale 3D printers at around $30,000. However, the drawback to this printer is that the build volume has been increased tremendously, while the print speed is that of an average desktop 3D printer. The 3D printer that the team will design can solve this problem by using more than one extruder, but should also have a similar build volume and price point.

Figure 4.1- BigRep One [1]

Another 3D printer with a large print volume is the Fortus 900mc, as seen in (**Figure 4.2**), made by Stratasys. However, this is an industrial 3D printer and far more expensive at around \$200,000. It has a build volume of 0.486m^3 with a resolution and positional accuracy of 178 microns and 90 microns, respectively. The advantage of the Fortus 900mc is the accuracy and reliability that come with such a high end 3D printer. The team hopes to achieve a similar level of accuracy and reliability with the team's final design, but at a fraction of the cost.

Figure 4.2- Fortus 900mc [4]

5. Functional Diagram

5.1 Introduction

A 3D printer has many different functions that need to be identified. To do this, a functional diagram must be made. This diagram is useful for identifying the main functional properties of a complex machine. In this case, a function is something that accomplishes a certain task in a process. The different functions all work together to accomplish the ultimate goal. Once the different functions are identified, the criterion of each function can be established to determine relative importance. The next section will show the functional diagram for a 3D printer.

5.2 Functional Diagram

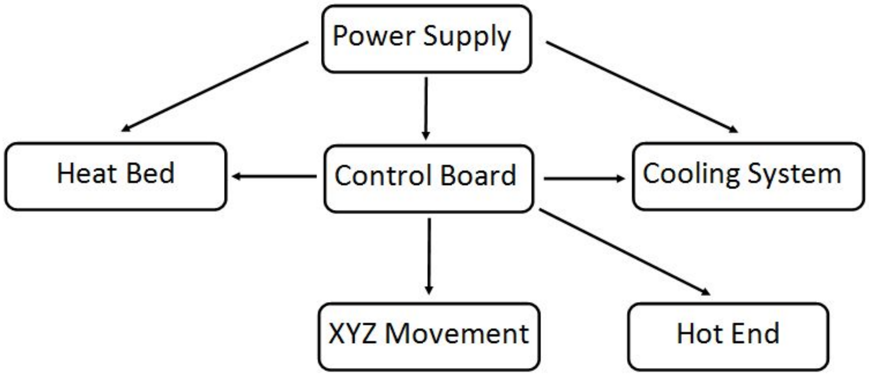


Figure 5.1- Functional Diagram

(**Figure 5.1**) shows the basic functional diagram for a 3D printer. Computer Programs, CAM and CAD tools, and firmware are more discrete sub functions of a 3D printer, but in regards to this functional diagram, the team decided to focus on the general functions of a 3D printer. These general functions include the power supply, heat bed, control board, cooling system, XYZ movement, and the hot end.

The power supply is the energy source of the 3D printer. In the United States, the voltage of a standard wall electricity output in a home is 120V. The main power supplies that 3D printers use are standard universal power supplies, ATX power supplies from computers, or any kind of power supply available that can support the proper wattage of the 3D printer system.

The heat bed is the platform in which the part is made. In larger scale models, a heated print bed is desired. The purpose of a heated print bed is to prevent the layers of the print from warping. This problem is prevalent in large print areas. For the bed to function, power must be supplied in order to generate heat.

The control board is what translates commands from the computer into movement of the printer, which is why XYZ movement branches off of the control board. The computer will communicate with the control board through various programs. These programs break a 3D model down into many layers and translate it into machine code called “G-Code”. The control board interprets the G-Code commands into movement of the various stepper motors, which in turn coordinates movement of the 3D printer extruder in the XYZ directions.

The cooling system is what keeps the 3D printer from getting too hot. Computer fans are often selected for the cooling process. These fans generate enough airflow to the hot end and prevent warping. Liquid cooling is also utilized in some 3D printers. The power supply also requires cooling often, but most power supplies include a fan pre-installed.

Finally, the hot end is the nozzle that melts the plastic filament in order to create each layer. These hot ends can often have up to 4 different nozzles that extrude different color filament. They can also have a single nozzle for a basic design. The control board will also communicate with the hot end to regulate heating temperature and extrusion rate. The client has specific requirements that the 3D printer which must be meet. The team must build and evaluate criteria for each function so that the 3D printer will meet the client’s specifications.

6. Criteria of Functions

6.1 Introduction

In order to create relative weights for the criteria, each team member did a piecewise comparison of the criteria for each function. The scale used can be seen in (**Table 6.1**). Our team’s six piece wise comparisons were then averaged to create our final weights for each criteria. These weights were then used in our decision matrix in section 7.3, to select the components for each function. Section 6.2 contains all of the piecewise comparisons, along with descriptions of the criterion.

Table 6.1- Criteria of Functions Scale

Judgement	Numbering
Extremely Preferred	9
Very Strongly Preferred	7
Strongly Preferred	5
Moderately Preferred	3
Equally Preferred	1

6.2 Relative Weights of Criteria

In (**Table 6.2**), the team established the criteria for the power supply as ease of implementation, power output, and cost. Ease of implementation is rated in terms of how much work needs to be done before it is ready to be implemented into the 3D printer and received a weight of 0.288. The power output was based upon how much power the power supply can output, and was weighted the heaviest at 0.462. Lastly, the cost was rated on how low the cost is and received a weight of 0.250.

Table 6.2 - Power Supply Weighted Criteria

Power Supply				
Criteria	Ease of Implementation	Power Output	Cost	Overall
Ease of implementation	0.167	0.432	0.263	0.288
Power Output	0.480	0.370	0.536	0.462
Cost	0.353	0.197	0.201	0.250

In (**Table 6.3**), the team established the criteria for the control system as open source, multiple motor drivers, and modular. Open source is based on the availability of code for the control board and whether we can modify existing code to fill our needs. This criteria was determined to be the most important and had a weight of 0.359. Next the multiple motor drivers was simply rated on how many stepper motors the control board can control and was weighted at 0.350. Lastly, modularity was based on how the control board was built, and whether individual components can be replaced or upgraded, and was weighted the lowest at 0.291.

Table 6.3 - Control System Weighted Criteria

Control System				
Criteria	Open Source	Multiple Motor Drivers	Modular	Overall
Open Source	0.156	0.378	0.542	0.359
Multiple Motor Drivers	0.579	0.153	0.318	0.350
Modular	0.265	0.468	0.141	0.291

In (**Table 6.4**), the team established the criteria for the hot end as temperature, nozzle size, and reliability. Temperature is rated on how high of a temperature the hot end can reach, and was weighted at 0.301. Nozzle size is based on how large of a diameter the hot end has, in our case a larger nozzle diameter is preferred. The nozzle size was determined to be the most important criteria and weighted at 0.365. Lastly, reliability was based on how consistent the hot end is and how resistant to clogging it is. This criteria was weighted at 0.334.

Table 6.4 - Hot End Weighted Criteria

Hot End				
Criteria	Temperature	Nozzle Size	Reliability	Overall
Temperature	0.204	0.255	0.444	0.301
Nozzle Size	0.448	0.219	0.430	0.365
Reliability	0.348	0.526	0.126	0.334

In (**Table 6.5**), the team established the criteria for the heat bed as temperature, cost, and speed. Temperature was based on how hot the heat bed can get and was given a weight of 0.236. Cost was based on how low the price of each heat bed is and was weighted the highest at 0.432. Lastly, the size was rated on the heat bed area, where a larger heat bed is preferred. The heat bed size was given a weight of 0.332.

Table 6.5 - Heat Bed Weighted Criteria

Heat Bed				
Criteria	Temperature	Cost	Speed	Overall
Temperature	0.118	0.196	0.394	0.236
Cost	0.537	0.286	0.472	0.432
Size	0.345	0.518	0.134	0.332

In (**Table 6.6**), the team established the criteria for the XYZ movement, which is comprised of the stepper motors. The criteria are torque, step angle, and revolutions per minute (RPM). These criteria were all based on the specifications for each stepper motor where torque and RPM are desired to be maximized, and the step angle is desired to be minimized. Torque was given the highest weight at 0.434, step angle was given a weight of 0.366, and RPM was given a weight of 0.200. With relative weights of each criteria established, the team then moved on to a their concept generation.

Table 6.6 - XYZ Movement Weighted Criteria

XYZ Movement				
Criteria	Torque	Step Angle	RPM	Overall
Torque	0.199	0.629	0.474	0.434
Step Angle	0.513	0.174	0.410	0.366
RPM	0.288	0.197	0.116	0.200

7. Concept Generation

7.1 Introduction

The concept generation section takes the information from the criteria of functions and finds products on the current market to fulfill such needs. This is called concept generation and is helpful in determining different types of solutions. Multiple products are chosen in order to have a diverse pool to choose from. These products are then ranked by means of decision matrices, which in all will pertain to the team's selection process of individual components.

7.2 Concept Generation

To begin the concept generation process, it is important to start at the heart of the project, the power supply. The power supply is critical in a 3D printer because it is what powers the whole system. The power supply needs to be able to have a wide range of input voltages, a high Watts power output, and finally a high Amp output. Keeping this criteria in mind, three power supplies have been chosen. The chosen power supplies are the ATX Power Supply, LED Strip Power Supply, and Universal Power Supply. Listed in (**Table 7.1**) below is each one of these power supplies as well as the common features. These common features include the power output, amps, and input voltage.

Table 7.1 - Power Supply

Power Supply	Power Output	Amperage	Input Voltage
ATX Power Supply	500W	16	115-230V
LED Strip Power Supply	480W	10	115-230V
Universal Power Supply	350W	29	110-220V

The next decision is to take a look at are control boards that are able to run the large scale 3D printer that Novakinetics needs. With many control boards on the market, the only boards to be considered are those that afford the most flexibility and expandability. These boards include the Azteeg X3 Pro, Smoothieboard, FastBot BBP, and finally an Arduino Mega. (**Table 7.2**) below list these control board as well as comparing specifications between the possible choices including the supported firmware, max number of stepper motors, and max number of thermistors.

Table 7.2 - Control Board

Control Board	Max # of Stepper Motor	Max # of Endstops	Max # of Thermistors	Firmware
Azteeg X3 Pro	8	6	3	Arduino IDE
Smoothieboard	5	6	4	Smoothie Firmware
FastBot BBP	6	5	3	Fastbot Firmware
Arduino Mega	4	6	3	Arduino IDE

(**Table 7.3**) contains three different stepper motors that can be used to build a large scale 3D printer. These motors include the RepRAP, Kysan 1124090, and Nema-17. Criteria for comparing the stepper motors are the running voltage, torque, and degree of step angle.

Table 7.3 - XYZ Movement

XYZ Movement	Running Voltage	Degree Step Angle	Max Speed	Torque
RepRAP	12V DC	1.8	200 RPM	0.48
Kysan 1124090	4.2V DC	1.8	400RPM	0.54
Nema-17	12V DC	0.9	600RPM	0.48

The hot end is important in determining both the resolution of a printed part as well as how long it will take to print. With this in mind three hot ends were selected for their reliability in other proven 3D printers. These hot ends include E3D Cyclops, E3D Volcano, and the MICRON3DP. Important specifications about each of these hot ends is listed below in (**Table 7.4**) and include the nozzle size and maximum temperature.

Table 7.4 - Hot End

Hot End	Nozzle Size	Max Temp.	Other Info
E3D Cyclops	.4mm	290 C	Multiple Material Feed
E3D Volcano	Multiple Sizes	290 C	up to +/-0.1mm accuracy
MICRON3DP	.35mm or .5mm	400 C	All Metal Hot End

In order to keep printed parts from warping during the printing process multiple heated print beds will be used in order to create one large heated print bed. The options include the MK2A, MK2B, and the Keenovo Heatbed. Their specifications of size and power input can be found below in (**Table 7.5**). With components selected, the team then began comparing each component using decision matrices.

Table 7.5 - Heat Bed

Heat Bed	Size	Power Input
PiBot Heatbed	250mm x 250mm	12V or 24V
MK2B Heatbed	214mm x 214mm	12V or 24V
MK2A Heatbed	214mm x 214mm	12V or 24V

7.3 Decision Matrices

The following section contains all the decision matrices and reasoning behind why a single product is a better in comparison to others. Starting with the selection of the power supply, the ATX power supply was given the highest weighted total and therefore is the best choice for this particular application. All of the power supplies were compared based on the criteria of ease of implementation, power output, and the cost and can be seen in (**Figure 7.6**). The ATX power supply received high ratings in cost because one of our teammates is able to get them for free. The power output also received high marks because it has the highest output of 500W. Ease of implementation is low because the ATX power supply is not plug-and-play. It will have to be modified in order to work for this particular application.

Table 7.6 - Power Supply Decision Matrix

Power Supply	LED Strip PSU		Universal Power Supply		ATX Power Supply	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Ease of Implementation (0.288)	7	2.02	9	2.59	6	1.73
Power Output (0.462)	8	3.70	6	2.77	10	4.62
Cost (0.250)	6	1.50	7	1.75	10	2.50
Weighted Totals:	7.212		7.114		8.848	

When comparing the control boards the clear winner is the Azteeg X3 Pro. By reference of (**Table 7.7**) it scored high in modularity and having multiple motor drivers. This is extremely important in being able to expand the printer later if changes need to be made. The Azteeg scored moderately in being open source because the board is only able to run basic firmware such as the Arduino IDE.

Table 7.7 - Control Board Decision Matrix

Control Board	Azteeg X3 Pro		Smoothie		Fastbot BBP		Arduino Mega Duet	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Open Source (0.359)	8	2.87	7	2.51	9	3.23	8	2.87
Multiple Motor Drivers (0.350)	10	3.50	6	2.10	7	2.45	5	1.75
Modular (0.291)	10	2.91	7	2.04	8	2.33	5	1.46
Weighted Totals:	9.282		6.650		8.009		6.077	

For the XYZ movement of the 3D printer the best suited stepper motor is the Nema 23-42BYGHM809. By having the lowest step angle this means that the Nema 17 will have a higher resolution and therefore the highest score. The RPM of the Nema 17 received the highest score due to it being the fastest. Torque was moderate and the score reflects this. The totals can be found below in (**Table 7.8**).

Table 7.8 - XYZ Movement Decision Matrix

XYZ Movement	RepRap Stepper Motor		Kysan 1124090		Nema 17-42BYGHM809	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Torque (0.434)	8	3.47	10	4.34	8	3.47
Step Angle (0.366)	5	1.83	5	1.83	10	3.66
RPM (0.200)	4	0.80	6	1.20	10	2.00
Weighted Totals:	6.102		7.370		9.132	

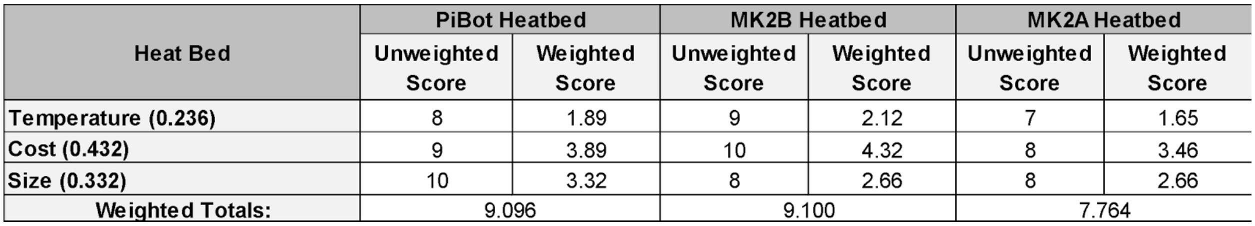
The hot end was a difficult decision. It came down to the Volcano having the highest scores in nozzle size as well as having good reliability. While the Volcano is not able to reach high temperature like the Micron 3DP it is still able to reach high enough temperatures to melt both PLA and ABS.

Table 7.9 - Hot End

Hot End	Cyclops		Volcano		Micron 3DP	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Temperature (0.301)	7	2.11	7	2.11	10	3.01
Nozzle Size (0.365)	6	2.19	10	3.65	5	1.83
Reliability (0.334)	8	2.67	8	2.67	7	2.34
Weighted Totals:	6.969		8.429		7.173	

When choosing the heat bed the MK2b heatbed is overall the best choice. It has very similar ratings compared to the PiBot. The deciding factor came down to how the weighted scores affected the unweighted scores and can be found in (**Table 7.10**) below. With components selected, the team began to construct a CAD model of their preliminary design.

Table 7.10 - Heat Bed



Heat Bed	PiBot Heatbed		MK2B Heatbed		MK2A Heatbed	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Temperature (0.236)	8	1.89	9	2.12	7	1.65
Cost (0.432)	9	3.89	10	4.32	8	3.46
Size (0.332)	10	3.32	8	2.66	8	2.66
Weighted Totals:	9.096		9.100		7.764	

8. Design

In (**Figure 8.1**) the preliminary design can be seen. In this design the X & Y gantry was supported by four guide rods and raised and lowered with four lead screws. The X-axis was controlled by a single stepper motor via a belt system, while the Y-axis was controlled by a single stepper motor with two shafts that connect to two separate belt systems to prevent binding. In (**Figure 8.2**) the scale of the 3D printer can be seen relative to an adult male. After consulting with Novakinetics, they expressed their desire to reduce the cost. With the preliminary design, the bulk of the cost was the four lead screws which cost $985 each. With this in mind, we began modifying the design to reduce the cost.

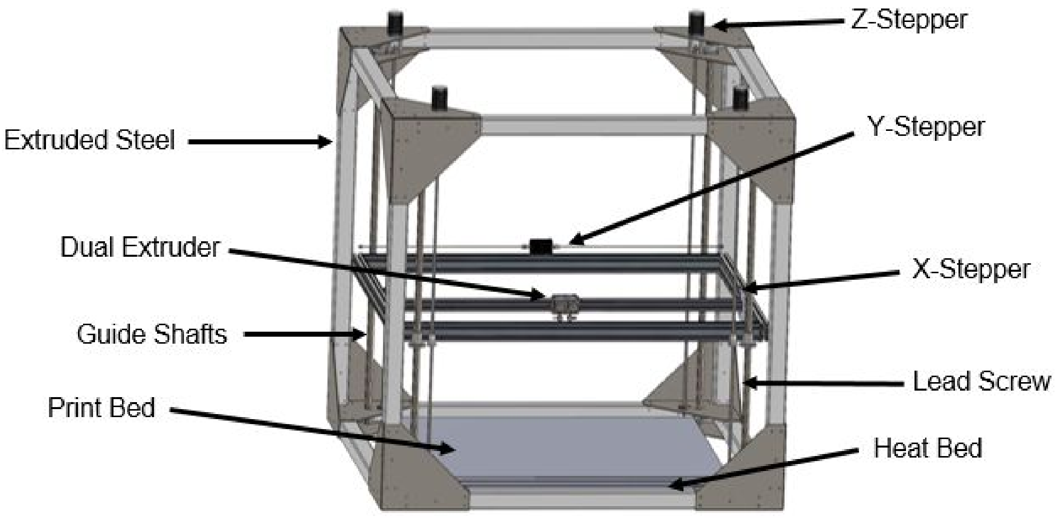


Figure 8.1 - Preliminary Design

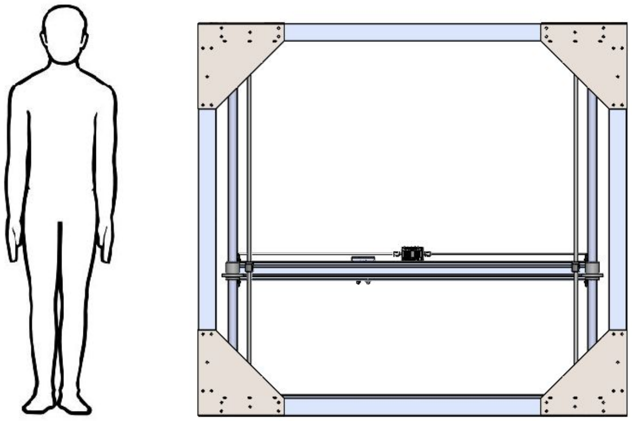


Figure 8.2- Relative size as compared to an average adult (~1770 mm)

In (**Figure 8.3**), the final design can be seen. The main difference between this design and the preliminary design is in how the print head is raised and lowered. In the preliminary design the print head was raised and lowered along with the entire gantry system, whereas in the final design the print head is raised and lowered via the Z-axis section of extruded aluminum. With this modification, the final design requires only one lead screw, which effectively reduced the cost by nearly $3,000.

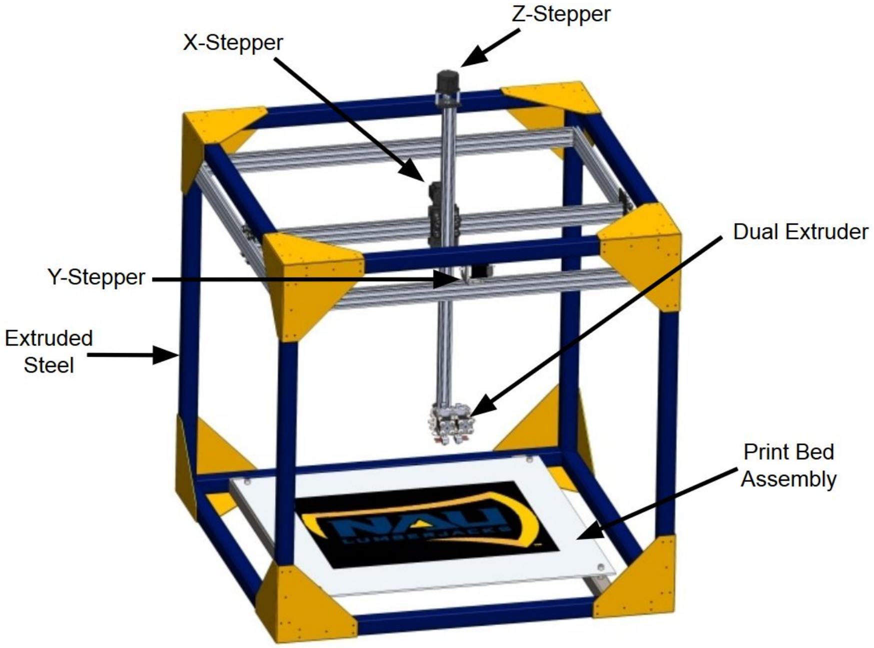


Figure 8.3 - Final Design

Once Novakinetics approved of the new design, sourcing of materials and components began. With all of the materials and components selected, the team made a series of purchase orders to begin the manufacturing process.

9. Bill of Materials (BOM)

9.1 Introduction

The bill of materials for the design has been broken up into multiple sections. These sections are the electrical components, the frame of the printer, the gantry system, and finally the miscellaneous components along with powder coating of the 3D printer. Each section will briefly cover what is listed in the BOM found in (**Table 9.1**). Finally the section will be concluded with a total cost of the printer.

Table 9.1 - BOM Electrical

Component	Product	Quantity	Total Price
X & Z Stepper Motors	Nema 23 23HS22-1504S	2	$112.85
Y Stepper Motor	Nema 23 WO-8718S-01	1	$139.00
Control Board	Azteeg X3 Pro	1	$233.50
Power Supply	Dell ATX Power Supply	1	$10.00
Computer	Dell Optiplex 755	1	$5.00
Print Head & Hot End	Dual-Head MK9	1	$119.00
Hardware	Miscellaneous Components	N/A	$167.72
TOTAL:			$787.12

The electrical section covers everything that will control the printer. This includes a main computer that will send commands to the Azteeg control board. The Azteeg control board will send signals that will control all of the other components listed in the BOM. The stepper motors were selected by performing calculations in order to decide the required holding torque needed for the X, Y, and Z axis. After completing the stepper sizing calculations for this large scale 3D printer, the Nema 23 was selected for both the X, Y, and Z axis. On the electrical side the most expensive parts include the stepper motors and the control board.

Table 9.2 - BOM Mechanical (Frame)

Component	Product	Quantity	Total Price
Outside Support Frame	Steel Square Tubing (2x2x13 GA)	12	$159.08
Fabricated Gussets	Steel Sheet Metal	36	$250.00
Total:			$409.08

The frame will be the least expensive system of the 3D printer according to (**Table 9.2**). The frame consists of structural support for the entire printer. The material selected for the frame was steel, as steel gives the greatest structural support for the weight of our gantry system. The gussets will also be made of mild steel. The total cost of the frame minus the additional hardware to fasten it together came out to be $409.08.

Table 9.3 - BOM Mechanical (Gantry)

Component	Product	Quantity	Total Price
Gantry Frame	2040 V-Slot Aluminum	5	$121.76
Cable Chain	N/A	5	$95.60
Belt	GT2, 5 mm	1	$125.24
Universal V-Slot Gantry Plate	Extruded Aluminum	4	$71.90
Hardware	Miscellaneous Components	N/A	683.75
Total:			$1098.25

The gantry system was the most expensive feature of the printer as seen from (**Table 9.3**). It will be made out of extruded V-Slot 6061 T5 aluminum. The V-Slot was chosen for this application because it is easy to maintain and is easy to add new features later on down the road as seen in the manufacturing section of this report. The most expensive parts are all the hardware needed to make the whole system work. The total cost of the gantry system came out to be $1098.25.

Table 9.4 - BOM Mechanical (Print Bed)

Component	Product	Quantity	Total Price
Heat Bed	Brisk Heat	1	$565.00
Print Bed	Extruded Aluminum	1	$221.48
Hardware	Miscellaneous	N/A	$103.40
Total:			$889.88

The Print Bed section was the second most expensive section of the 3D printer with the heating bed being its most expensive component as found (**Table 9.4**). Due to the vast size of the printer a large heating bed was required in order to evenly distribute heat to the aluminum bed. Other components of the assembled print bed included the print bed itself, steel beams and hardware to assemble it together. The total cost of the print bed came out to be $889.88

Table 9.5- BOM Powder Coating & Miscellaneous

Component	Product	Quantity	Total Price
Miscellaneous	Computer Mount & Filament	N/A	$590.21
Powder Coating	N/A	N/A	$300.00
Total:			$990.21

With the main sections of the 3D printer priced, other miscellaneous components such as filament for test printing, extra fasteners and bolts, a computer mount for the control system, and finally the powder coating of the printer were then accounted for in (**Table 9.5**). The total price for this section came out to $990.21.

Table 9.6- BOM Total

Section	Cost
Frame	$409.08
Gantry	$1098.25
Print Bed	$889.88
Electrical	$787.12
Powder Coating	$300.00
Miscellaneous	$590.21
Total:	$4074.54

After compiling all of the costs for the six different sections the total cost comes out to be $4041.66 and the breakdown can be seen in (**Table 9.6**).

10. Manufacturing

To begin the manufacturing process, the 3D printer was divided into sections that could be manufactured separately and then assembled to achieve the final product. The sections of manufacturing are the print bed, frame, gantry system, and lastly the electrical components.

10.1 Print Bed

The manufacturing of the print bed is fairly straightforward. The process begins with a 38x38x⅜ inch plate of 6061 aluminum as seen in (**Figure 10.1**).

Figure 10.1 - Aluminum Plate

With this plate of aluminum, four half inch holes are drilled in the corners (**Figure 10.2**) to allow the aluminum plate to be fastened to two sections of two inch square steel tubing. This is done by using half inch bolts along with high stiffness springs which provide dampening and allow the print bed to be leveled.

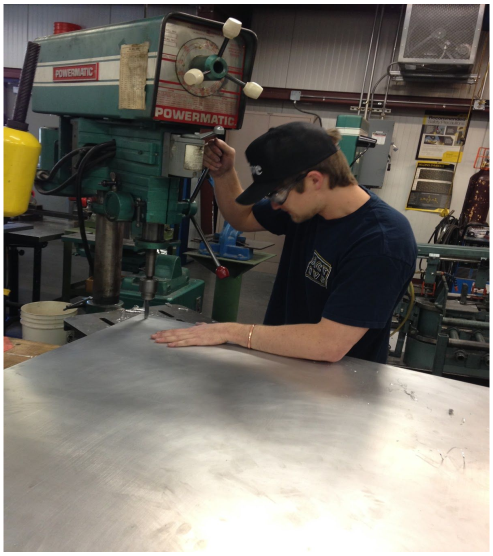


Figure 10.2 - Print Bed Drilling

With the holes drilled into the print bed, the 24 inch by 36 inch heat bed is installed with adhesive as seen in (**Figure 10.3**) below. This heat bed is capable of reaching temperatures in excess of 230C, which is well above the print temperature of 100C that it will be operating at.

Figure 10.3 - Aluminum Plate With Heat Bed

One issue that was encountered with the print bed was a slight warping of the aluminum plate. The team plans to address this by installing braces to apply tension and flatten out the surface. With the print bed assembly completed, manufacturing of the frame proceeded.

10.2 Frame

The manufacturing of the frame was broken down into three different stages. The first stage consisted of acquiring all necessary materials. The materials needed for this stage were 12 2”x2”x1/8” square steel tubes, 24 six gauge steel gusset plates, and all the hardware (nuts, bolts, casters, etc). After acquiring the materials, stage two began.

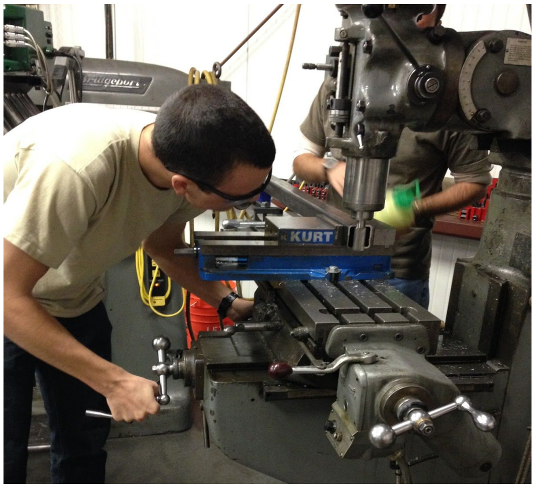


Figure 10.4 - Face Milling

In stage two of manufacturing the frame, the main focus was the fabrication of the parts of the frame. This included tasks such as drilling holes, facing ends, deburring edges, and cleaning the parts. This was perhaps the most time consuming of each of the three stages. For all of the beams, 240 through-holes were needed to be drilled and each end needed to be faced down to specifications. (**Figure 10.4)** shows the end mill set up for the facing operation and (**Figure 10.5)** shows the deburring operation, which was one step in the process of cleaning each part.

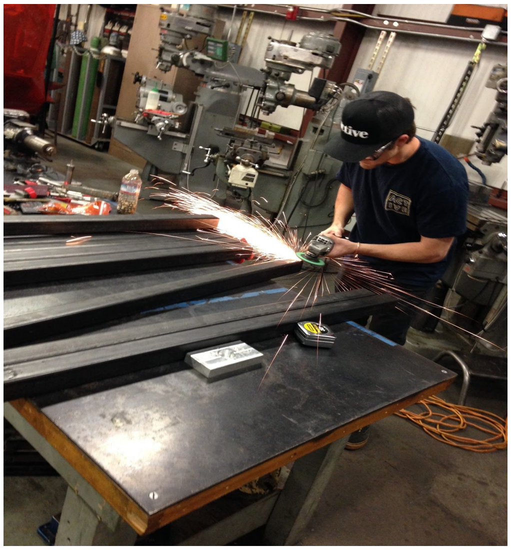


Figure 10.5 - Deburring

Once the parts had been fabricated, the assembly of the frame could begin. As can be seen in (**Figure 10.6**), the frame is a cubic structure that is composed of 12 beams and 24 gusset plates, each held together by nuts and bolts. Also, due to the large number of bolts required for assembly, a specific process was needed to follow in order to assemble the frame correctly. First, the top and the bottom four beams were assembled separately and on the ground by the use of the gusset plates on each corner. They were then connected together with the four vertical beams, which completed the cubic shape.

Once the frame had been assembled, some tweaks needed to be made. First, due to tolerances, the frame wobbled slightly when placed on the ground. To fix this, the bolts were loosened then strategically tightened while ensuring the frame was as square as possible. Also, since the frame weighs a significant amount at this point, it was necessary to install casters onto the bottom to allow for transportation of the frame. The final assembly of the frame can be seen in (**Figure 10.6**).

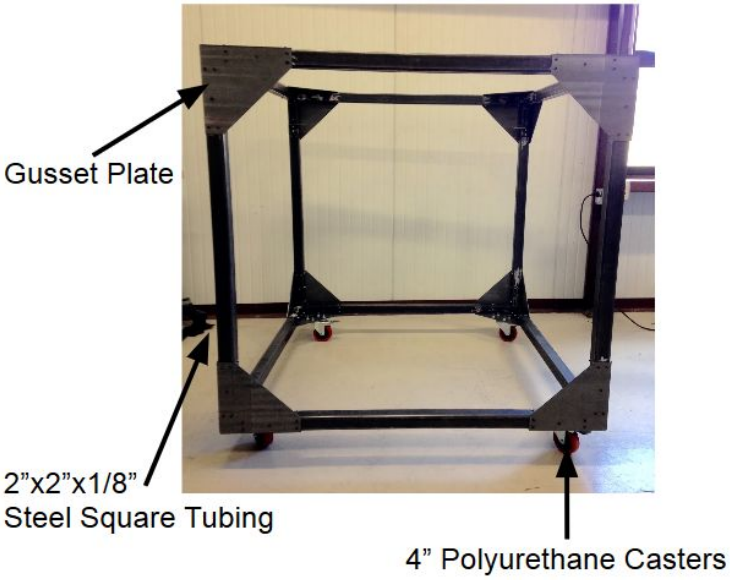


Figure 10.6 - Final Frame Assembly

10.3 Gantry

In Fall 2015, the team decided to go with the v-slot gantry setup. The V-slot beams used are made of extruded aluminum and are the support structure of choice when it comes to accurate and precise movement as well as interchangeability. The profile of the V-slot extruded aluminum allows for mounting of different components. The team decided to use this because it is lightweight and capable of interchangeability as well as capable of accurate movement. Openbuilds Parts Store was the vendor of choice for the Gantry system because they had very good support for custom 3D printer builds and parts could be individually bought. This allowed the team to get creative with the design as well as be able to support it effectively in the future with replaceable parts. The size of the V-slot extruded aluminum was chosen to be 20mmx60mm. (**Figure 10.7)** shows the profile of the V-slot extruded aluminum.

Figure 10.7 - V-Slot Extruded Aluminum Linear Rail

When four of these extruded aluminum linear rails are connected at each ends, they create a large square area where a systematic X and Z system can be placed. (**Figure 10.8)** shows four V-Slot extruded aluminum linear rails connected together to create the main structure for the gantry. (**Figure 10.9)** shows the roller plates that will be used to move the X and Z movement apparatus around.

Figure 10.8 - Gantry Rail Setup

Figure 10.9 - Polyurethane roller wheel

Polyurethane wheels with roller ball bearings were then attached to aluminum plates to create a moving structure within the gantry. The gearing system that will drive the Y movement of the 3D printing apparatus will be placed on this supporting gantry structure. This involves a polyurethane belt, a drive gear, and an idler pulley situated on each side of the X and Z moving apparatus. A dual axial Nema 23 Stepper motor will drive this belt and drive system which will move the X and Z apparatus with precision.

Using the Polyurethane wheels and mounting plates, a V-slot extruded aluminum linear rail was mounted through the middle of the square frame. This will allow the framework for the X and Z directional apparatus to be made. (**Figure 10.10**) shows the square framework with the X and Z movement apparatus attached to it using the polyurethane roller plates.

Figure 10.10 - X and Z movement apparatus

This is the final design for the gantry which was assembled in the machine shop. As you can see in (**Figure 10.10**), the Z movement is determined by a lead screw design and guided by a plate with 6 polyurethane roller wheels guiding the aluminum rail. Each stepper motor provides movement in the X, Y, or Z direction respectively. The Gantry, once it was completed, was then placed into the Frame of the 3D printer.

10.4 Computer Shelf & Filament Holder

In order to mount the computer and control system, a steel shelf was fabricated and mounted to the back of the frame as seen in (**Figure 10.11**).

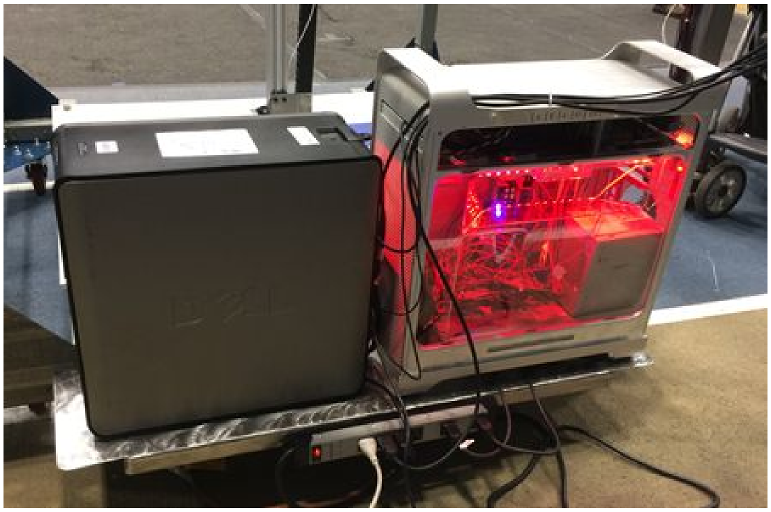


Figure 10.11 - Control System

To hold the filament a filament holder was fabricated and mounted to the top of the frame. It is designed to hold up to two 10kg rolls. The filament holder can be seen in (**Figure 10.12**).

Figure 10.12 - Filament Holder

10.5 Electrical

Work on the electrical system started with the acquisition of a Dell desktop from property surplus. The desktop is used to slice the models from solidworks files into G-code. This is handled with the Repetier-Host program that the group installed in the Dell. The slicer program that comes with Repetier is called Slic3r. Both Repetier and Slic3r are established programs in the 3D printing community and offer support and expandability for future upgrades. Another reason why Repetier was selected was because of the easy implementation with the selected control board.

The selected control board is the Azteeg X3 Pro. This control board supports expandability for upgrades in printer design such as adding more steppers to change the configuration of the printer. The Azteeg X3 Pro is also compatible with the Repetier-Host program through the utilization of the Repetier firmware. Ounce the team received the Azteeg control board the firmware was flashed to the board.

The firmware files are of importance especially for this project because it allows the user to select advanced features. One of these features is changing the number of print heads from the default of one to two. Learning how the firmware works was also key to understanding how the control board works in general. The code is written in the Arduino IDE and makes for easy understanding.

After the firmware was installed on the board the motor drivers needed to be setup. The purchased NEMA 23 motors have a maximum current rating of 2 amps. In order to prevent damaging the stepper motors the current was limited on the drivers through the use of a turnable trimmer. This trimmer can be seen in (**Figure 10.13**) below. After the current limits were all set for the X, Y, & Z steppers heat sinks were then added to the top of the drivers. Another heat sink was attached on the bottom of the board across all of the MOSFETS used to control the extruders and other accessories.

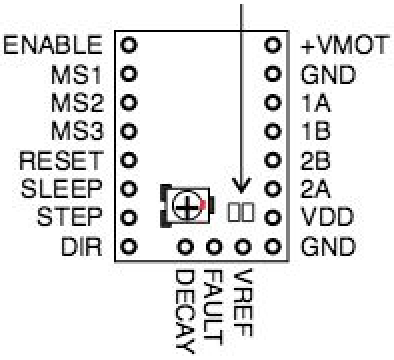


Figure 10.13- Diagram of Stepper Driver

At this point the electronics could now be tested. For testing purposes the team got 2 12V ATX power supplies along with a generic 12V computer fan. Testing started by first following the wiring diagram found below in (**Figure 14**). Once everything was wired the control board was turned on and then connected to the Repetier-Host program. The fan was positioned to provide maximum air flow over the heat sinks. Basic settings were inputted into the configuration section of the Repetier-Host program. This allowed us to move the steppers and determine everything was working properly.

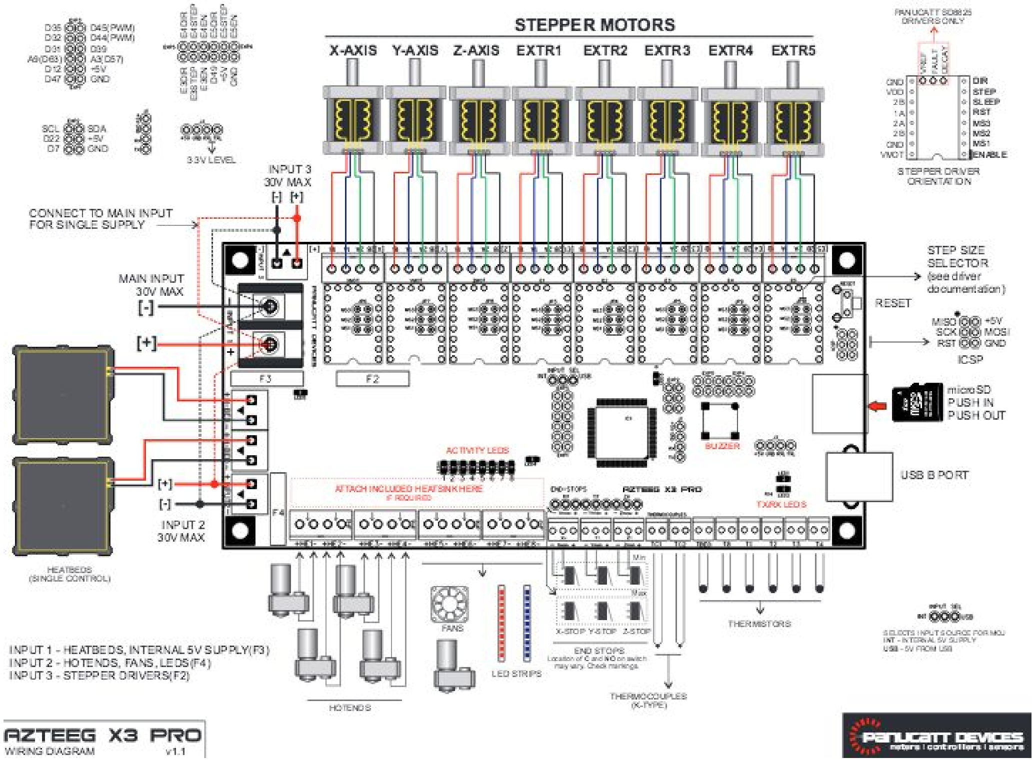


Figure 10.14 - Azteeg X3 Pro

After testing the electronics it became clear that there was a need for a control box in order to clean up and organize the wiring. To do this a chassis was need in order to protect the control board and organize the wiring. An Apple G5 computer was selected to make up the chassis. All of the Apple components were stripped out of the G5 except for the built in 12V 14 Amp with dedicated fans were left in place and will be utilized to supply power to the Azteeg board. Specifically it will be supplying power to the Azteeg's logic board. Standoffs were built into the case and allowed us to mount the Azteeg stood off the back surface of the case. This will allow for good airflow around the board and heatsinks. A terminal block assembly was then installed on the bottom in order to facilitate clean wiring between the Azteeg board and all the accessories such as stepper motors, end-stops, and thermistors. This will prove useful in troubleshooting the machine as well as general maintenance and replacement of broken parts. The completed control system can be seen below in (**Figure 10.15**).

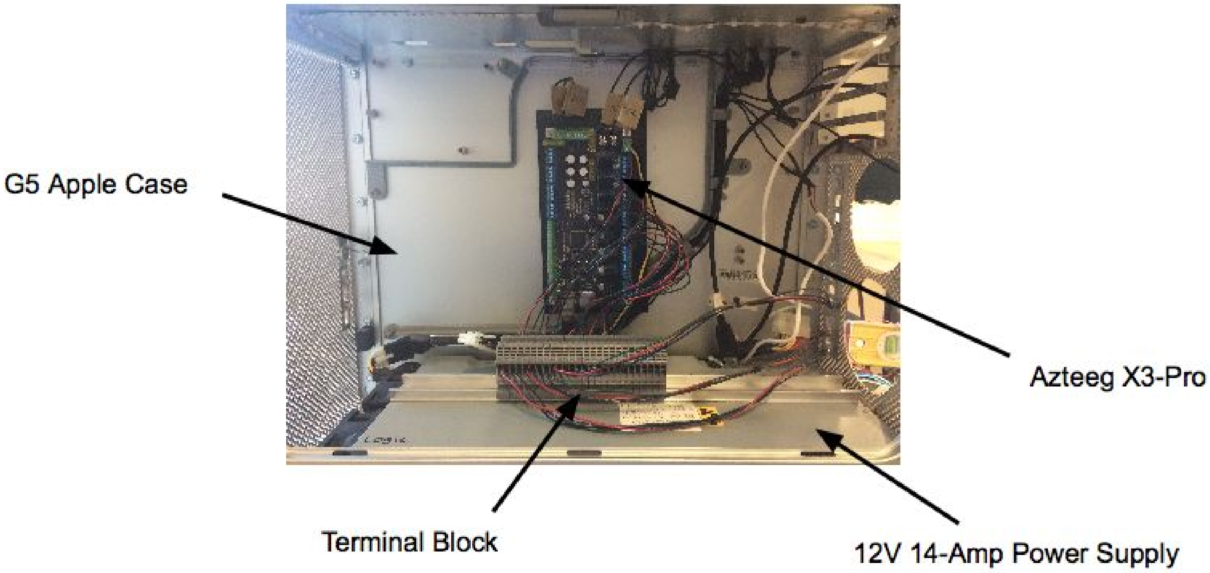


Figure 10.15 - Layout of The Control System

10.6 Design Modifications

Design modifications were made to the 3D printer in order to print objects better. Originally, the print bed was not completely level. To compensate for the irregular geometry, the print bed was coated in epoxy. This will allow for modifications in the future to smoothen out the irregularities in the print bed. (**Figure 10.16)** shows the print bed with epoxy applied to the surface.

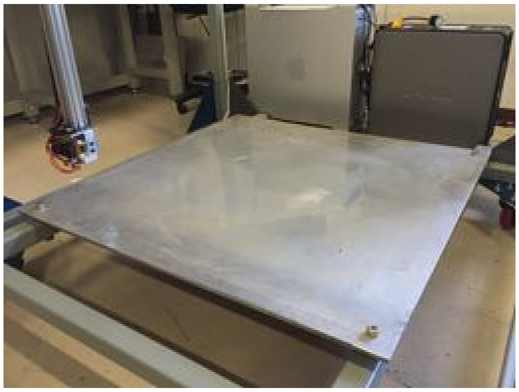


Figure 10.16 - Epoxy added to Print Bed

To compensate for oscillations in the Z arm of the 3D printer, a larger V-Slot beam was implemented. The gantry was changed from a 20 x 60 mm V-slot rail to a 40x40 mm V-slot rail. This was applied to the X arm and the Z arm. This reduced the oscillations by a 2 millimeters in the Y direction. This made the printer print more smoothly and created better quality prints while strengthening the gantry system. **Figure 10.17** shows the 20x60 mm rail next to the implemented 40x40mm rail.

Figure 10.17 - 20x60 V-Slot Rail to 40x40 mm V-Slot Rail

10.7 Completed Assembly

The final additions to the 3D printer included Cable Management and a workstation where a user can work directly from the printer. Cable Chains were added as well as a computer monitor and keyboard stand. **Figure 10.18** shows the 3D printer in its completed stage of assembly.

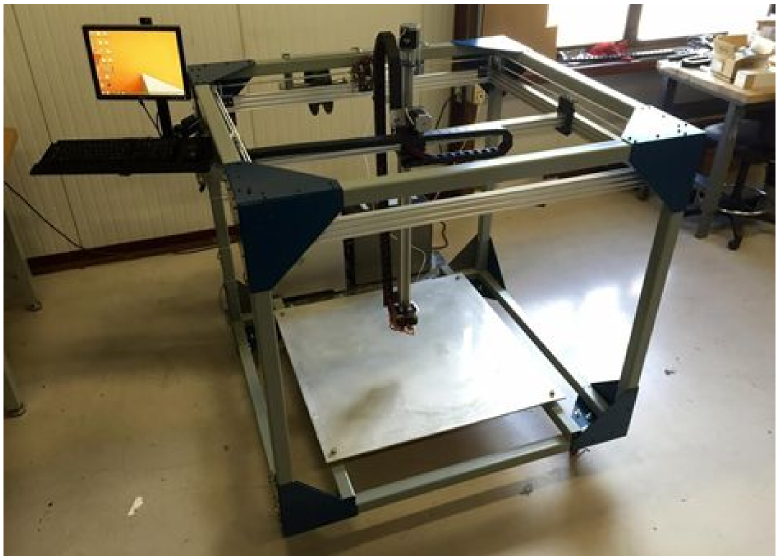


Figure 10.18 - Completed Assembly

11. Performance Testing

After the printer was assembled, several prints were made to calibrate the 3D printer. (**Figure 11.1**) shows the machine printing a 25x25 mm calibration cube. Cubes are common for 3D printer Calibration and show if the linear gantry movement matches the movement required for the print. Calibrations within the program were made to match the movement with the desired print lengths. (**Figure 11.2**) shows the a completed calibration cube.

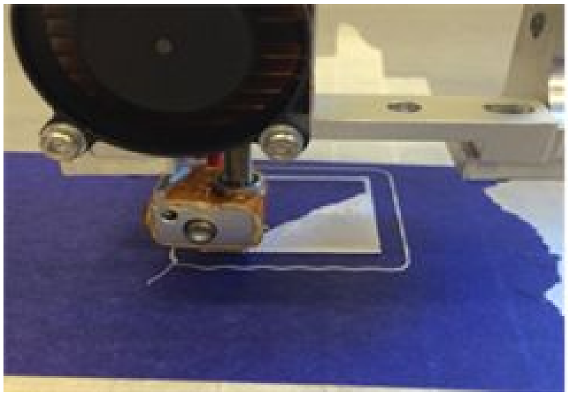


Figure 11.1 - 3D Printer Calibration

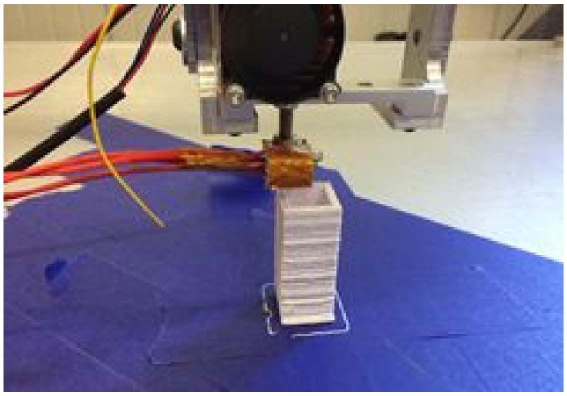


Figure 11.2 -Rectangular Print

After Calibration, full size prints can be made. A 3D model can be loaded up into Repetier and the computer can properly scale the part needed to be printed. From there, the machines make the Stepper Motors move in the directions required to make the print. (**Figure 11.3**) shows the Printer printing a battle axe.

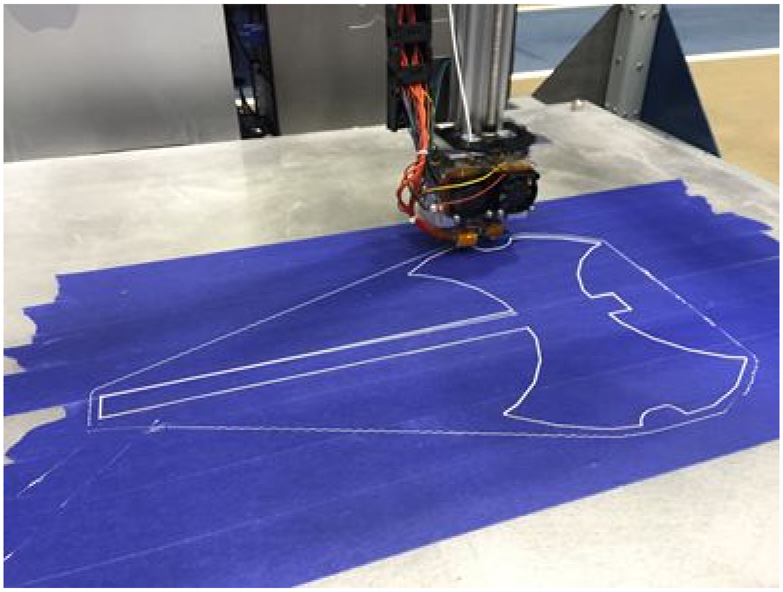


Figure 11.3 -Battle Axe Print

The 3D printer was able to print a battle axe that was 2 ft. by 1.5 feet. Blue tape was used so that the print would stick to the print bed properly. The printer was also able to print at a speed of 25 mm/second. This met the goal of our project and meets the design criteria of the client Novakinetics.

12. Conclusion

The client is Novakinetics, a company based in Flagstaff that specializes in aerospace composite parts. They are currently in need of a more efficient manufacturing process in order to reduce the lead time for molds and tooling. This can be achieved using 3D printing by optimizing the process for large scale printers while maintaining affordability. The objectives therefore are to increase the print speed, maximize accuracy, reduce maintenance, make it safe to operate and easy to use, as well as economic. The major constraint for this project is the print volume, which must be larger than 1m^3. Through a QFD and SOTA, the team established objectives that their 3D printer design must meet. To create such a design, the team identified key operating functions using a functional diagram. For each function, criteria was established which were given relative weights using a piecewise comparison. With established relative weights for each criteria, the team then researched individual components in relation to each function. Decision matrices were then formed to rank and compare the individual components based on how well they met each weighted criteria. Using these decision matrices, the individual component selection process began.

The power supply the team decided to use is an ATX power supply due to it being the most affordable and having the highest power output. For the control board, the Azteeg X3 Pro was selected due to being the most modular and being able to run the most amount of stepper motors for expandability down the road. To address the general XYZ movement of the printer, the Nema 23-42BYGHM809 stepper motor was selected due to possessing high holding torques and being able to run at fast speeds. Finally, the printer's heat bed will be custom built using a large 24"x36" heat mat and 38"x38"x ⅜" 6061 aluminum plate. With selected parts chosen, the next step as seen in the team's project plan is to design and create a CAD model of the 3D printer in order to prove the design validity and functionality.

Using SolidWorks, the team was able to design a CAD model of their 3D Printer as apparent in the preliminary design section of this report. After designing the CAD model, the next step was to construct a bill of materials of the main components necessary to build this 3D Printer. When constructing this bill of materials, the team decided to split it up into 5 main sections, an electrical, frame, gantry, print bed and finally a miscellaneous system section. After summing all of the component prices of each section, the total costs were as follows: Electrical: $787.12, Frame: $409.08, Gantry System: $1098.25, Print Bed: $898.88, and Miscellaneous:$990.91. Ultimately, the overall cost of the team's 3D Printer came out to be $4374.54. With a CAD model and Bill of Materials completed, the next step for the team is to manufacture, assemble and test the 3D Printer.

To begin the manufacturing process, the team divided the 3D printer into sections that could be manufactured separately and then assembled to achieve their final product. The sections of manufacturing include the print bed, frame, gantry system, and lastly the electrical components. In regards to the mechanical components of the 3D Printer, after configuring the frame, gantry, and print bed such components were then fastened together and the mechanical assembly portion of the team's 3D printer was completed. In consideration to the electrical components of the 3D printer, a control system enclosure was assembled, followed by the calibration and programing of the stepper motors and printer. During the manufacturing process, design modifications included increasing the surface flatness of the print bed by coating it in a thermally stable epoxy followed by changing the X-axis bar to one with of a larger cross sectional area to address vibrations as seen during initial tests. With the main components of the 3D printer assembled and design modifications addressed, other sub components installed on the 3D printer included the computer shelf and mount, filament holder and finally cable chains. After performance testing, the 3D printer was a success as it was capable of printing a variety of objects ranging from a cube to a battle axe.

13. References

[1] Bigrep.com, 'BigRep | Large Scale 3D Printing', 2015. [Online]. Available: http://bigrep.com/bigrepone/. [Accessed: 19- Sep- 2015].

[2]B. Millsaps, 'Kloner 240TWIN 3D Printer', *3DPrint.com*, 20 15. [Online]. Available: http://3dprint.com/63633/kloner-3d-240twin/. [Accessed: 20- Sep- 2015].

[3] Novakinetics.com, 'Composite Manufacturing Products', 2015. [Online]. Available: http://www.novakinetics.com/. [Accessed: 20- Sep- 2015].

[4] Stratasys.com, 'Fortus 900mc 3D Prototyping Machine', 2015. [Online]. Available: http://www.stratasys.com/3d-printers/production-series/fortus-900mc. [Accessed: 19- Sep- 2015].

[5]S. Bhandari, '3D Printing and Its Applications', *Saveetha School of Engineering*, 2014.

[6]'The Free Beginner’s Guide To 3D Printing', *3D Printing Industry*, pp. 3-72, 2015.

[7] 3ders.org, 'how to build 3d printer', 2015. [Online]. Available: http://www.3ders.org/3d-printer/how-to-build-3d-printer.html. [Accessed: 18- Oct- 2015].