Next Generation 3D Printer

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Project Proposal

Document

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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 (NT) 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 but are limited by production time and print size. 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 overcome 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 NT has established the objectives to increase the print speed, maximize accuracy, reduce maintenance, make it safe to operate and easy to use, and be economical. With a design that can overcome such limitations, the NT 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 of the NT’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 3D printing.

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 dimension. Resolution is the fidelity of the printed part. 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, 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 can be formed.

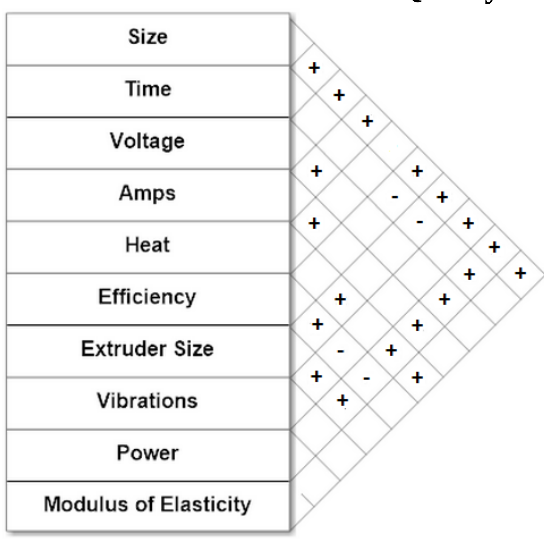
Table 3.1: QFD

		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 is 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



3.4 Project Plan

The project plan as seen in Table 3.3, is what the team is planning on following in order to accomplish this project on time. The project plan is broken up into three distinct sections that correspond to the progress of the projects. The first is colored blue and represents the problem definition stage. The next section is purple and represents the design phase. With the help of both the QFD and HOQ, several designs will be proposed and with the help of a decision matrix one design will be chosen. This design will move into the final section of the project plan. This section is colored red and represents the prototyping and testing phase. The prototype will test the validity of the chosen design and will help to further refine the design to a final state. Important dates are located at the bottom of the project plan and will be used to remind the team of upcoming due dates. Now that the team knows what the client wants, the team will then conduct research in order to gain a better understanding of what is currently available on the market. The next section will discuss benchmarking and the relevant products that are already on the market.

Table 3.3: Project Plan

	Task / Week	Week 1	2	3	4	5	6	7	8	9	10	11	12	13
1	Meet With Client													
2	Define Project Objectives and Constraints													
3	Decision Matrix													
4	Quality Function Deployment													
5	Research Designs													
6	Research Coding Techniques													
7	Flow Chart For Coding													
8	Select Final Design													
9	Create CAD Models													
10	Select Materials/Components													
11	Estimate Cost													
15	Finalize Project Proposal													
	Project Definition and Project Plan Presentation		9/21/2015											
	Concept Generation and Final Decision Presentation								10/19/2015					
	Proof of Concept Demonstration												11/16/2015	
	Project Proposal													12/7/2015

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.

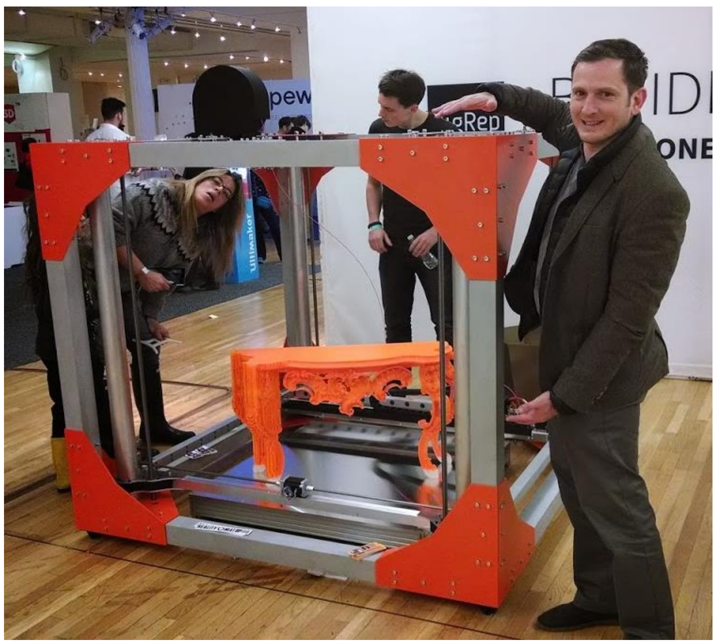


Figure 4.1: BigRep One

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

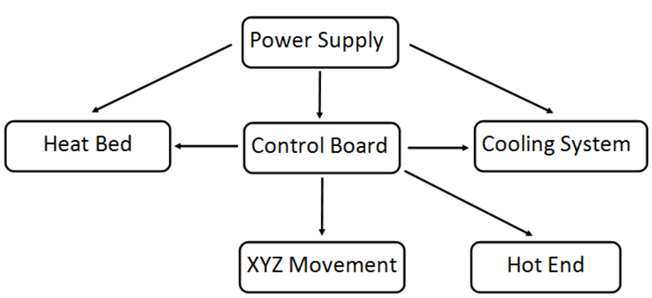


Figure 5.1: Functional Diagram

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, the heat bed, the control board, the 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. Some 3D printers utilize glass as the print surface. 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 must 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

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				
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				
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				
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				
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.

Table 6.6

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

In Table 6.7, the team established the criteria for the cooling system to be efficiency, power consumption, and cost. Efficiency is based on how fast the cooling system can remove heat, and was given the highest weight at 0.381. Power consumption was based on the amount of power required for the cooling system and was given a weight of 0.272. Lastly, the cost was based on the price for each cooling system and given a weight of 0.347. With relative weights of each criteria established, the team then moved on to the concept generation.

Table 6.7

Cooling System				
Criteria	**Efficiency**	**Power Consumption**	**Cost**	**Overall**
Efficiency	0.195	0.445	0.502	0.381
Power Consumption	0.307	0.121	0.389	0.272
Cost	0.498	0.434	0.109	0.347

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 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

The cooling systems main job is to keep the extruder cool in order to prevent clogging. Its secondary job is keep both the control board and stepper motors cool in order to extend their life-cycle. Three different and unique types of cooling systems were chosen as possible solutions.

These included the EK-Water Cooling, Corsair AF140 fan, and the Addicore Heatsink. Corresponding specifications of the cooling method and unit cost can be found in Table 7.5.

Table 7.5: Cooling System

Cooling System	Cooling Method	Unit Cost
EK - Water Cooling	Forced Convection	$224.99
Corsair AF140 Fan	Forced Convection	$20.99
Addicore Heatsink	Natural Convection	$4.55

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 7.6. With components selected, the team then began comparing each component using decision matrices.

Table 7.6: 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. 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 7.7 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 7.8 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 7.8 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 17-42BYGHM809. 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.

Table 7.9: 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 7.10: 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	

The cooling system was very close across the board. Overall the Corsair AF140 fan is the winner because of receiving good rating in all categories of efficiency, power consumption, and cost.

Table 7.11: Cooling System

Cooling System	EK - Water Cooling		Corsair AF140 Fan		Addicore Heatsink	
	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Efficiency (0.381)	10	3.81	8	3.05	5	1.91
Power Consumption (0.272)	9	2.45	8	2.18	10	2.72
Cost (0.347)	5	1.74	9	3.12	10	3.47
Weighted Totals:	7.993		8.347		8.095	

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. With components selected, the team began to construct a CAD model of their preliminary design.

Table 7.12: 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. Preliminary Design

In the past several years, 3D printing has become increasingly more popular. As a result of this, many designs have emerged for numerous applications and environments and have either been geared toward hobbyists or professionals. In the initial stages of designing this 3D printer, the team faced many difficulties, mainly due to the large scale of the printer. After considering the requirements and constraints, the team determined that the most effective and efficient design would be simplistic, versatile, and reliable. Extensive research into what currently exists led the team to decide on a cubic design due to its structural integrity, its ease of access, and its upgradeability.

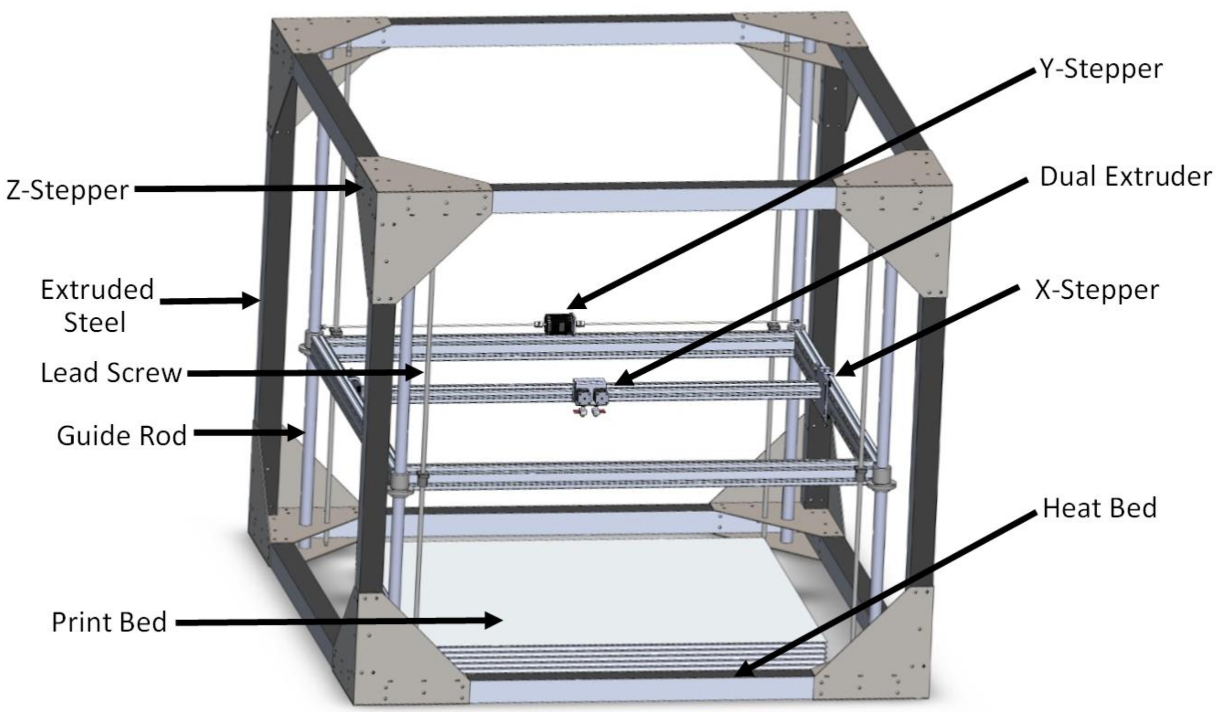


Figure 8.1: Major Components

As seen in Figure 8.1, the cubic design is composed of a large steel frame with an extruded aluminum gantry system. This design utilizes a total of five stepper motors which control each of the three axes (X, Y, and Z), as well as the dual extruders on the print head. The Z-stepper drives four lead screws (one in each corner) through the use of an intricate belt system. Due to the fact that the lead screws are not structurally sound on their own, a guide rod is mounted near each of the lead screws. The Y-stepper, through the use of a dual sided drive rod, drives two belts, one on either side of the gantry system. Each belt is attached to a corresponding side of the carriage. The X-stepper is mounted on the carriage and it drives a single belt that moves the print head along its length. The print bed has a precision-machined aluminum surface and is heated by four heating elements installed beneath the surface.

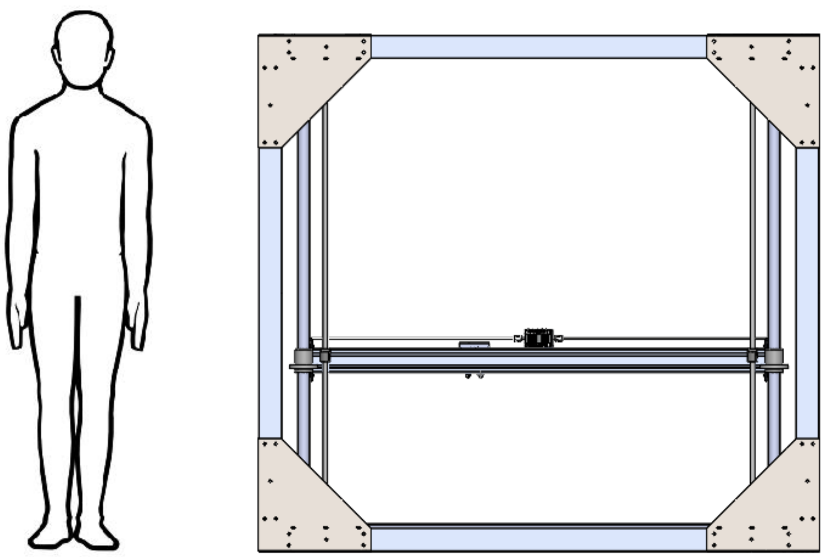


Figure 8.2: Relative size as compared to an average adult (~1770 mm)

With such a large print volume, it is clear that the frame of this printer should be quite large as well. In Figure 8.2, the relative size of the printer can be seen as compared to an average adult. Figure 8.3 displays the major dimensions of the frame as well as the potential print volume. At these dimensions, the print volume is approximately 2.17 cubic meters, which is more than twice the required print volume. If necessary, the printer can be scaled down to accommodate budget, space, or materials. Considering this size, the team decided upon a design which maximizes the ease of operation, maintenance, and assembly/disassembly. The first stage of assembly is putting together the frame which is mainly comprised of steel square tubing, laser cut steel gussets, and steel bolts. The second stage of assembly is the gantry system, which is made of extruded aluminum. Once the gantry system has been assembled and installed into the frame, the third stage of assembly can be completed, which consists of mounting all electrical components.

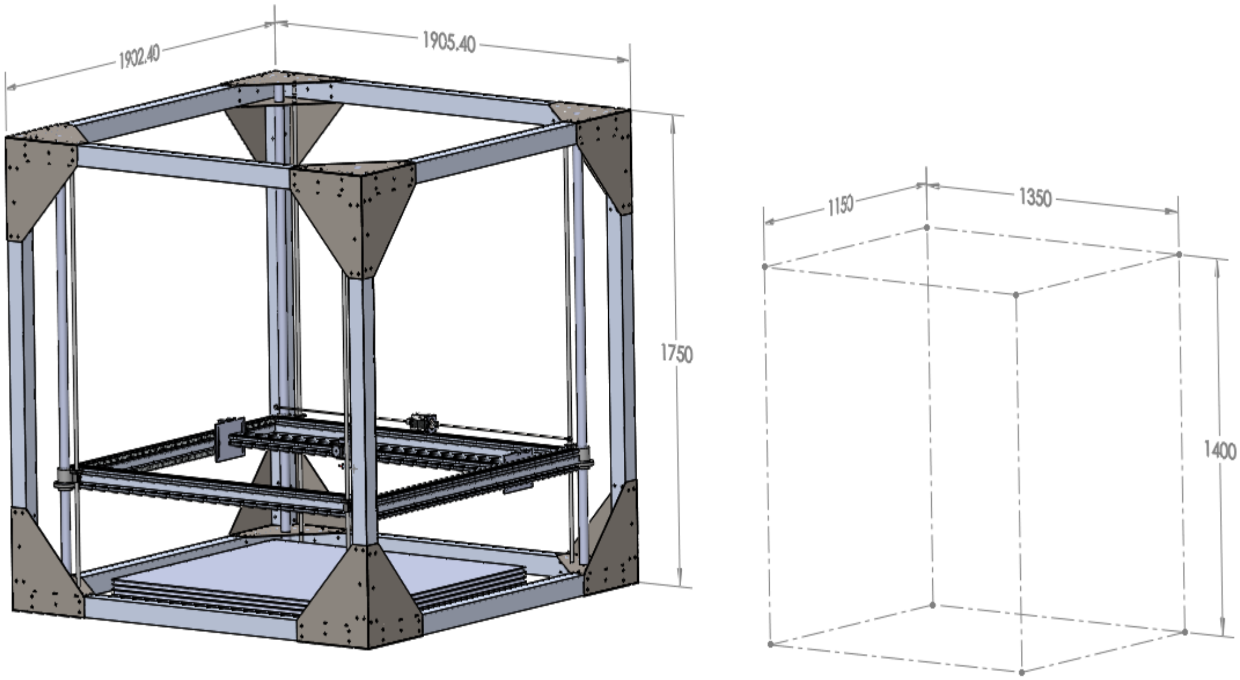


Figure 8.3: Major dimensions and print volume (all units are in millimeters)

9. Bill of Materials (BOM)

9.1 Introduction

The bill of materials for our design has been broken up into multiple sections. These sections are the electrical components, the frame of the printer, and then the gantry system. Each section will briefly cover what is listed in the BOM. Finally the section will be concluded with a total cost of the printer.

Table 9.2: BOM Electrical

Component	**Product**	**Quantity**	**Price (Dollars/Unit)**	**Total Price (Dollars)**
Stepper Motor	Nema 23 23HS22-1504S	2	$16.00	$32.00
Stepper Motor	Nema 34 WO-8718S-01	1	$139.00	$139.00
Heat Bed	Keenovo	4	$69.99	$279.96
Control Board	Azteeg X3 Pro	1	$220.00	$220.00
Hot End	E3D Volcano	2	$55.00	$110.00
Power Supply	Dell ATX Power Supply	1	$10.00	$10.00
Computer	Dell Optiplex 755	1	$5.00	$5.00
Print Head	Dual-Head MK9	1	$189.67	$189.67
TOTAL:				$985.63

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 and Y axis, instead of a Nema 17. Similarly a Nema 34 was selected to move the gantry system up and down due to. On the electrical side the most expensive parts include the stepper motors, heat bed, and the control board.

Table 9.3: BOM Mechanical (Frame)

Component	Product	Quantity	Price (Dollars/Unit)	Total Price (Dollars)
Outside Support Frame	Steel Square Tubing (2x2x13 GA)	12	$26.22	$314.64
Fabricated Gussets	Sheet Metal (Mild Steel)	36	$10.50	$252.20
Guide Rods	Multipurpose 6061 Aluminum Rods	4	$75.66	$302.64
Gantry Lead Screws	Lead Screws	4	$96.43	$385.72
Hardware	Fasteners	N/A	N/A	~$200.00
Total:				$1455.20

The frame will be the most expensive system of the 3D printer. The frame consists of structural support for the entire printer as well as the hardware required to fasten the support together. 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 guide rods are made of multipurpose 6061 aluminum rods, which are common for guide rails. These guide rods will ultimately be emplaced to help take the overall load from the leadscrews. Along with the support structures required to create the 3D printer Frame, Fasteners are required to keep the supports in place. The team averaged the cost for fasteners to be around $200.00. The total cost of the frame came out to be $1455.20, but will be slightly more than that price due to shipping costs and tax.

Table 9.4: BOM Mechanical (Gantry)

Component	Product	Quantity	Cost (Dollars/Unit)	Total Price (Dollars)
Gantry Frame	2040 V Slot Extruded Aluminum	5	$19.50	$97.50
Y Movement Rod	Stainless 316 Steel	2	$6.16	$12.32
Extruder Carriage	Aluminum	1	$85.00	$85.00
Gantry Bracket	Universal V-Slot Gantry Set	2	$35.95	$71.90
Hardware	Belts, Pulleys, Fasteners, V-Slot Wheels, Mounts	N/A	N/A	~$150.00
Total:				$416.72

The gantry system will be the second most expensive feature of the printer. 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. The aluminum will be the second most expensive part under the gantry system. 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 $416.72, but will be slightly more than that price due to shipping costs and tax.

Table 9.5: BOM Total

Section	Cost
Electrical	$795.96
Frame	$1455.20
Gantry	$416.72
Total:	$2857.55

After compiling all of the costs for the three different sections the total cost comes out to be $2857.55. This cost is not including tax, shipping, or labor costs.

10. 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.

In consideration to the power supply, the team decided to use 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 stepper motors. For the hot end, the Volcano was selected due to it being to have the largest nozzle. To address the general XYZ movement of the printer, the Nema 23-42BYGHM809 and Nema 34 stepper motors were selected due to possessing high holding torques and being able to run at fast speeds. The team’s cooling system will consist of multiple Corsair AF140 fans due to their low cost. Finally, the printer’s heat bed will be custom built using multiple Keenovo heat beds due to their ability to reach high temperatures and being the most affordable. 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. According to this model, this 3D printer's print volume will be a little over $2m^3$. This volume doubled that of originally expected. 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 3 main sections, an electrical section, a frame section and finally a gantry system section. After summing all of the component prices of each section the total costs were as follows: Electrical: $985.63, Frame: $1455.20, Gantry System: $416.17. Ultimately, the overall cost of the team's 3D Printer came out to be $2857.55; however, this total amount is still on the conservative side and will change over time as the team did not include shipping, tax and manufacturing costs in calculating this total amount. With a CAD model and Bill of Materials completed, the next step for the team is to construct and program their 3D Printer. The manner in which the team will go about constructing this 3D Printer will consist of the following steps. The first step is to build the frame, next, the gantry system will be assembled and installed, and finally, the electrical components will be added and programmed. This will all be accomplished next semester.

11. References

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