Rapid Prototyping - 3D Printer

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by

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ABSTRACT

The 3D printing world has been in its infancy and has been growing in there last few years. However, with all of the growth there has not been a printer that would get the best out of both cost and build size. The following design is able to do so. Using general shop and fabrication practices this printer design is a low cost and large envelope 3D printer for personal or commercial use.

An engineering group was surveyed to determine the needs of a 3D printer. The group surveyed showed that Reliability, Easy to Use, and Accuracy are the main components that are desired in a 3D printer. Design concepts were thought of to attain the concepts and using product development methods a Open design concept was accepted. This would allow for easy maintenance and a more compact design for the printer.

With the design set the designer looked to determine the lead screw forces needed to life and lower the load. This was based on Acme Lead Screw calculations and designed for accuracy and a smooth movement. The X and Y axis motors were selected based upon the GatesDF program which gave the correct horsepower and torque required to move the components used in printing.

As a result parts that are used for this printer will need to be able to use as a solid concept that can be a test fit and allow for accurate conclusions of the design to be done. The parts created will measure out to the dimensions of the solid models ±.005. This will show an accurate depiction of the solid model in the real world. The frame will be comprised of steel and powder coated to keep rust from forming. The filament for the printer will need to be feed cleanly to obtain the reliability of the printer and to maintain the efficiency of the printer.
INTRODUCTION

In the fast paced world of business reducing the time to market keeps you ahead of your competition. Having the capability to reduce design iterations between engineering and sales/marketing allows new products to get to market faster. Being able to take advantage of 3D printing can also reduce Engineering R&D material costs as well as labor cost. Having the ability to make a functioning part that can be used to check fit/form/function in hours rather than days allows for a more flexible design process. 3D printing has been increasingly growing in usage since 2003, but the cost has not come down enough in order for small market companies to use the technology.

Current personal desktop 3D printers have a smaller 5” cube, which reduces the number of parts that can be made with the printer. By increasing the size envelope of the printer company’s can increase the amount of parts that can be made. The proposal is to design a cost effective 3D printer that can create parts within a 10-12” cube. Fecon Inc. will supply the funding for the project and will use the printer as an R&D tool for product development.

MAIN COMPONENTS OF A 3D PRINTER

The general components of a 3D printer are relativity the same from one to the other. Below is Figure 1 that will show the main components of the 3D printer and will give a brief explanation of what the components are used for in the daily function of the printer.
The 3D printer is comprised of Motors, Rails, Heating Elements, Platforms, Belts, and Filament. The main purpose of the Motors, Rails, and Belts are to provide motion for the three axis of movement for the printer X-Y-Z. Those motors are in connection with a mother board (Not Shown) that takes signals from a computer connected through USB to the printer. This allows for the precise movement of the heating Element at the top of the printer to pull in Filament in order to melt the plastic into the exact location that is needed to produce a physical model from a 3D program. The filament is usually PLA or ABS plastic both of which are used commonly in 3D printer applications. The build platform is used to hold the build table that is heated using PCB board to allow for proper placement of the filament on the table. In general these components are used in multiple variations by different companies to make a 3D printer. Depending on the range of wants by the customer it can reduce or improve cost in the product. There are several different manufactures that make 3D printers for either personal or commercial use in the marketplace.

EXISTING PRODUCTS

The 3D Printer has caught on as a viable way to develop rapid prototypes for company and personal use. While the vast majority of technology has expanded the price for a large envelope machine has maintained its high cost and has been out of reach for mid level companies.

In the research that was completed there are several examples of large commercial 3D printers such as the Dimension 1200es Series (1) machines that have an envelope of minimum of 10” x 10” x 12 inches (1). However the large size of the machine and the price of around $24,900 (1) is a high price for a company to sink into and it not cover the cost of the machine for years to come.

Figure 2 - Dimension 1200es Series
With this the research continued and the next machine that was found was the Zcorp 3D Printer. This machine has a smaller starting price tag of $14,900 (2), but with the smaller price tag comes a smaller envelope.

The Makergear Mosaic 3D printer is a cost effective printer that has a build envelope of 5” x 5” x 5” (3). It comes in a kit that cost $989.00 (3) in which they send to you with most of the electrical components assembled and they leave you to do the build up of the machine. This makes the assembly a bit tedious and in some instances discourages an individual during the build of the machine. They also leave it up to the end user to find a place for the power converters which cause a hazard once the unit is complete as they just lay anywhere around the unit once it is in use. This unit also leaves it up to the end user to find a way to properly allow the filament to feed into the system without binding and causing errors in the printed model.
Another personal printer is the Botmill unit which comes in at $999.00 (4) and has a build envelope of 8” x 8” x 5” (4). This unit while it has a larger envelope at about the same price as the Makergear Mosaic based on the Figure 2 (3) it looks very complicated to build and to maintain the leveling of the machine.

Figure 5 – Botmill 3D Printer

The Makerbot Replicator 3D printer which comes to the end user as a completely built unit and makes the setup of the machine quite simple. It comes in at a cost of $1,749.00 (5) and a build envelope of 8.9” x 5.7” 5.9” (5) which is still smaller than that of a large commercial unit in which the project will be completed for.

Figure 6 – Makerbot Replicator 3D Printer
FEATURE SURVEY AND RESULTS

The engineering group at FECON was surveyed to determine what features would be the most important in the 3D printer that would be used. The department consists of eight individuals composed of Engineers and engineering co-ops. The survey covered a range of topics such as cost, maintenance/service, Build time, and accuracy. The results of the survey were put into a QFD (Quick Function Diagram), which allows the designer of the 3D printer to evaluate and determine how the end design will operate for the end customer.

![Table 1](image)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Customer Importance</th>
<th>Designer’s Multiplier</th>
<th>Modified Importance</th>
<th>Relative weight</th>
<th>Relative weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELIABLE</td>
<td>4.9</td>
<td>1.0</td>
<td>4.9</td>
<td>0.12</td>
<td>12%</td>
</tr>
<tr>
<td>ACCURATE</td>
<td>4.4</td>
<td>1.0</td>
<td>4.4</td>
<td>0.11</td>
<td>11%</td>
</tr>
<tr>
<td>EASY TO USE</td>
<td>4.3</td>
<td>1.0</td>
<td>4.3</td>
<td>0.10</td>
<td>10%</td>
</tr>
<tr>
<td>COST EFFECTIVE</td>
<td>3.8</td>
<td>1.1</td>
<td>4.2</td>
<td>0.10</td>
<td>10%</td>
</tr>
<tr>
<td>EASY TO MAINTAIN</td>
<td>4.1</td>
<td>1.0</td>
<td>4.1</td>
<td>0.10</td>
<td>10%</td>
</tr>
<tr>
<td>SAFE</td>
<td>3.9</td>
<td>1.0</td>
<td>3.9</td>
<td>0.05</td>
<td>9%</td>
</tr>
<tr>
<td>PLUG N PLAY</td>
<td>3.4</td>
<td>1.1</td>
<td>3.7</td>
<td>0.05</td>
<td>9%</td>
</tr>
<tr>
<td>EFFICIENT</td>
<td>3.0</td>
<td>1.1</td>
<td>3.3</td>
<td>0.08</td>
<td>8%</td>
</tr>
<tr>
<td>EASY TO BUILD</td>
<td>2.8</td>
<td>1.1</td>
<td>3.1</td>
<td>0.07</td>
<td>7%</td>
</tr>
<tr>
<td>COMPACT</td>
<td>2.8</td>
<td>1.0</td>
<td>2.8</td>
<td>0.07</td>
<td>7%</td>
</tr>
<tr>
<td>QUIET</td>
<td>2.3</td>
<td>1.2</td>
<td>2.8</td>
<td>0.07</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 1 – Customer Importance

The feature of Reliability (12%) came in with the largest customer importance as well as the largest relative weight when the designer’s multiplier was added. The designer felt that the surveyed results showed that the level of reliability was at an adequate level for the feature. Just as the accuracy (11%) and easy to use (10%) features were highly valued during the survey there is no need for the designer to increase the importance. The feature of cost effectiveness (10%) did need some designer input into improving the importance of the cost of the printer. If the printer is not cost effective then there is no need to get it or other options may be explored.

Having the unit easy to maintain (10%) was a feature that got a high survey result, which lead the designer to leave that unaffected. The unit design would lead to not having a high maintenance cost and would allow for minimal adjustments needed after the first initial setup. The next two features were safety (9%) and Plug N’ Play (9%) the designer looked at other units on the market and felt that the safety of the unit can be accurately shown with warnings to not go toward the machine while in use and felt the surveyors gave it an accurate score in terms of importance. When the designer looked into the other units on the market the Plug N’ Play feature was one the designer considered a place for improvement. Looking at others on the market some leave items out in the open and not in a compact unit with
minimal outside connections. The efficiency (8%) of the unit was another trait that was
looked to be improved by the designer. The units out there leave it up to the end user to
come up with a way to hold the filament which can lead to problems with the model as the
plastruder can leave gaps in the model and hurts efficiency.

The last three features Easy to Build (7%), Compact (7%), and Quiet (7%) all had a low
rating with the surveyors. The designer looked at these features to improve the printer
overall and still maintain the function of the printer and customer satisfaction. Having the
unit easy to assemble will only help the end user enjoy the product. Also the printer will
work in a office environment in a typical fashion so having a quiet unit that doesn’t cause
distractions is very beneficial.

**PRINTER DESIGN OBJECTIVES**

The following objectives’ are shown in order of importance as shown in Table 1, which
are needed to perform the function of a 3D printer. The objectives are paired with
engineering characteristics that with allow the design to be measured upon completion of the
project. Using engineering characteristics will facilitate a good sound design and determine
the best feasible solution to the design problem.

1. RELIABLE (12%)
   a) Machine will print without the presence of a person
   b) Filament will feed cleanly and without binding.

2. ACCURATE (11%)
   a) Parts created will measure out to the dimensions of the solid models ±.005.

3. EASY TO USE (10%)
   a) Operator will be able to operate machine with a procedure of less than 10
      steps.

4. COST EFFECTIVE (10%)
   a) Prototype cost will be $2000-$3000.

5. EASY TO MAINTAIN (10%)
   a) Bed will only need level checks annually by using basic hand tools
   b) Frame will be powder coated to prevent rust

6. SAFE (9%)
   a) Shafts of motors will have guards
   b) Exposed wires will be loomed
   c) Power supply’s will be enclosed in the unit
   d) Will calculate load rating on Motors to assure they don’t exceed the motor
      limit.

7. PLUG N’ PLAY (9%)
a) Machine will turn on by plugging in one plug and flipping a switch.
b) Files will be maintained on a network connected to a computer/laptop.

8.) EFFICIENT (8%)
a) Software will allow configuration to have any model to print in less than 10 hrs.

9.) EASY TO BUILD (7%)
a) Machine will be made of subassemblies to allow for assembly with basic hand tools.
b) Unit Assembly time will be below 5 hours.

10.) COMPACT (7%)
a) Machine will not take up more space than a desktop printer.

11.) QUIET (7%)
a) Unit will be covered to reduce noise levels.

**ENGINEERING CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Garrett Ford 3D Printer</th>
<th>Dampening/Sound Method</th>
<th>Power Supply (V)</th>
<th>Build Table Weight (lb)</th>
<th>Materials</th>
<th>Print Setup Time (Min)</th>
<th>Overall Weight (lb)</th>
<th>Build Envelope</th>
<th>Metal Finish/Color</th>
<th>Filament Applicator</th>
<th>Manufacturability</th>
<th>Leveling Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELIABLE</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACCURATE</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASY TO USE</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COST EFFECTIVE</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASY TO MAINTAIN</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
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<tr>
<td>SAFE</td>
<td>1</td>
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<td>3</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLUG N’ PLAY</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFFICIENT</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASY TO BUILD</td>
<td>3</td>
<td></td>
<td></td>
<td>3</td>
<td>9</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPACT</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUIET</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abs. importance 1.10 1.22 1.26 1.58 1.44 1.64 1.82 2.25 3.33 4.51 4.50 24.7  
Rel. importance 4% 5% 5% 6% 6% 7% 7% 9% 14% 18% 18% 1.0

Table 2 – Engineering Characteristics
For the engineering characteristics and emphasis was put on the reliability and accuracy based on the surveys from the customer. There are several of the characteristics that were put into the QFD that would affect both the reliability and the accuracy. Both the filament apparatus and leveling method will affect the apparatus due to the fact that how the filament is fed through the heating element and the table that is under the element will help in the quality of parts that are a product of the printer. If the filament is not fed smooth then the prints will not fuse together well and will come apart.

The metal finish and the build envelope are also a contributing factor in the design of the printer. The build envelope needs to be big enough for common parts to not need to be scaled down. This also leaves the ability for components to be tested before actually being made with expensive materials. This reduces time to market and give the ability for iterations to be done less expensively.

CONCEPT GENERATION AND SELECTION

With the surveys complete and features ordered with the importance the designer looked to have concepts to look through to allow for a selection of the best concept to use as the final design.

The concepts were based on looking at a variety of the other printers on the market. The first concept will be referred to as the Closed Design. This is because the design will be closed up and no parts will move outside of the housing. This will help with controlling the sound and keeping the unit quiet, but will not allow for easy access to maintenance of the machine. The closed design will also cause the unit to become increasingly bigger as it must be able to account for the 12” build envelope that will be used for the printer. With the large envelope the printer will also weigh more than the second concept, which will increase the cost of the printer and make it less cost effective than the other.

![Figure 7 – Closed Design Concept](image-url)
The second concept design will be referred to as the Open Design. This design will allow for easy access to maintenance items and also have a smaller footprint due to the fact that the printer bed will allow for the free movement of the bed without restriction of the surrounding housing. This concept however does cause a safety issue and must be labeled adequately in order to keep individuals from getting hurt during the operation of the printer. Also this design will allow for less material thus resulting in the reduction of cost.

![Figure 8 – Open Design Concept](image.png)

The design concept was chosen using the weighted rating method and thus given adequate weights based on the Customer surveys. The concepts were then rated using a five-point scale (0-4) and then multiplied by the weight to find the total score of each concept. In this instance the Open design gained the higher number and was chosen to move on to the design and manufacturing steps in the project.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Weight</th>
<th>Rating</th>
<th>Closed Design Weighted Rating</th>
<th>Open Design Weighted Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable</td>
<td>0.12</td>
<td>3</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Accurate</td>
<td>0.11</td>
<td>3</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Easy to Use</td>
<td>0.10</td>
<td>3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Cost Effective</td>
<td>0.10</td>
<td>1</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Easy to Maintain</td>
<td>0.10</td>
<td>1</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Safe</td>
<td>0.09</td>
<td>3</td>
<td>0.27</td>
<td>0.18</td>
</tr>
<tr>
<td>Plug N’ Play</td>
<td>0.09</td>
<td>3</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>Efficient</td>
<td>0.08</td>
<td>3</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Easy to Build</td>
<td>0.07</td>
<td>2</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>Compact</td>
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<td>1</td>
<td>0.07</td>
<td>0.21</td>
</tr>
<tr>
<td>Quiet</td>
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<td>4</td>
<td>0.28</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>1</td>
<td></td>
<td><strong>2.46</strong></td>
<td><strong>3.04</strong></td>
</tr>
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</table>

Table 3 – Waiting Rated Method Results
CALCULATIONS

CALCULATING LEAD SCREW FORCES

The design of the lifting mechanism for the build table was built on the principle of the lead screw and using the force of an electric motor to develop the required torque in order to lift the build table to the appropriate level for use. By finding the total weight of what is to be lifted the motor specifications can then be found. The Density of PLA plastic which is a common used material in rapid prototyping is 0.0477 lb/in$^3$ (7).

$$P = W_{Gantry} + W_{Model}$$

$W_{Gantry} = \text{Weight of Build Platform and Components}$

$W_{Model} = \text{Weight of Model being built}$

$W_{Gantry} = 15 \text{ lbs}$

The model weight is based on a solid 6” cube which is:

$$\text{Volume of 6” cube}=6*6*6 = 216 \text{ in}^3$$

$$\text{Weight of 6” cube made out of PLA} = 216 \text{ in}^3 * 0.0477 \frac{\text{lb}}{\text{in}^3} = 10.3 \text{ lbs}$$

Safety Factor = 2

$$10.3 \text{ lbs} * 2 = 20.6 \text{ lbs}$$

$W_{Model} = 20.6 \text{ lb}$

$$P = 15 \text{ lbs} + 20.6 \text{ lbs} = 35.6 \text{ lbs}$$

The lead screw is a precision acme threaded rod with a standard size of 3/8”-8 and a speed ratio of 4:1. This will allow for a larger range of movement as 1 turn will move ½” of linear rotation. The ANSI B1.5-1988 standard (7) is used to find the torque required to raise and lower a load. The torque required to lift the load is from the equation:

$$T_R = \frac{Fd_m}{2} \left( \frac{l + \pi f d_m}{\pi d_m + f l} \right)$$

Using the Calculator that is found at the Mead Info website and inputting the design data:
$d_m = 3/8''$

Load = 35.6 lbs

$\mu = 0.8$

Number of Thread starts = 4

The Results were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Diameter of Lead Screw, $d_{major}$ (Inches)</td>
<td>3/8</td>
</tr>
<tr>
<td>Threads per Inch</td>
<td>12</td>
</tr>
<tr>
<td>Load, $F$ (Lb)</td>
<td>35</td>
</tr>
<tr>
<td>Coefficient of Friction, $\mu$</td>
<td>0.6</td>
</tr>
<tr>
<td>Thread Angle, $2\alpha$</td>
<td>29</td>
</tr>
<tr>
<td>Number of Thread Starts</td>
<td>4</td>
</tr>
<tr>
<td>Mean Diameter of Lead Screw, $d_{mean}$</td>
<td>0.333</td>
</tr>
<tr>
<td>Load, $L$</td>
<td>0.333</td>
</tr>
<tr>
<td>Lead angle</td>
<td>17.66</td>
</tr>
<tr>
<td>Torque To Raise The Load (Lb-In)</td>
<td>6.82</td>
</tr>
<tr>
<td>Torque To Lower The Load (Lb-In)</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Figure 9 – Acme Calculator Results

It is typical for electric motors to be rated in oz.-In so a conversion is necessary for the output from the calculator due to the units being Lb-In. One Lb-In equals 16 Oz-In

Torque Required to Raise the Load:

$$6.82 \text{ lb-in} \times \frac{16 \text{ oz-in}}{1 \text{ lb-in}} = 109.12 \text{ oz-in}$$

Torque Required to Lower the Load:

$$1.47 \text{ lb-in} \times \frac{16 \text{ oz-in}}{1 \text{ lb-in}} = 23.52 \text{ oz-in}$$

**Calculating Load Forces on the Build Platform**

The design of the build platform is also a part of the design that needs to be checked to make sure that the weight of the models will not distort the build platform causing problems with the printer during operation. The following analysis was done using Solidworks
Simulation and the inputs that were put into solidworks were as follows.

The unit went through a static analysis of the amount of load that the build plate will undergo during the most extreme situation. Figure 10 shows the fixed geometry of the unit which are the guide rails and the lead screw.

![Figure 10 – FEA Fixed Geometry](image)

The load was then applied to the unit. As calculated above the load in the most extreme case would be ~36 lbs. Figure 11 shows the load being applied to the top of the guide rail carrier. While the build table will be larger than the 12” cube the unit will be designed for the amount of load will all fall on the guide rail carrier.

![Figure 11 – FEA Load Conditions](image)

The results yielded a max stress of around 6.3 ksi in a small section on the bottom of the unit in the worst case scenario. This was deemed adequate by the designer and found to be negligible due to the fact that the stress is only located in a small section of the model whereas the rest of the model was not above 2.1ksi. The design also received a safety factor of 1.8 which coincides with the calculated safety factor of 2.
From here the designer looked to the displacement of the model based on the given load. Figure 13 shows the displacement of the model which did not exceed 0.001” of an inch. It is important to note that the max displacement occurred on the outside edge due to the fact that the load was not applied directly in the center of the rail.

CALCULATING TORQUE AND HORSEPOWER FOR X & Y AXIS MOTORS

From the Sli3er software the average acceleration of the X and Y axis motors is 2000 mm/s². Given the acceleration the designer then found the velocity of the belt and then the design RPM.

\[ a_c = \frac{v^2}{r} \]
Converting Rev/s to RPM:

\[
2.81 \text{ rev/s} = \frac{1 \text{ RPM}}{0.0166 \text{ rev/s}} = 168 \text{ RPM}
\]

Using the Gates DFpro program the designer inputted the calculated RPM needed to move the X and Y axis. The program yielded the results that a motor with the equivalent horsepower of 0.003 would be adequate to move both the X and Y axis components. Calculating the torque needed to move the X and Y axis the designer took the 168 RPM and calculated the horsepower.

\[
T = \frac{P_{hp} \times 63025}{n}
\]

\[
T = \frac{0.003 \text{ hp} \times 63025}{168 \text{ rpm}} = 1.125 \text{ lb} - \text{in}
\]

Converting lb-in to oz-in:

\[
1.125 \text{ lb} - \text{in} \times \frac{16 \text{ oz} - \text{in}}{1 \text{ lb} - \text{in}} = 18 \text{ oz} - \text{in}
\]

With those results the designer found a 19 oz-in Motor to be used for both the X and Y axis motors. Motor specifications can be seen in Appendix H.

**ASSEMBLY DESIGN DETAILS**

**The Frame**

The frame for the 3D printer will be made of steel and bent and welded into together. The unit will weight approximately 73 lbs when fully assembled. The components were designed for a stationary office environment. It will be powder coated to be rust resistant and maintain a presentable appearance. The frame will also have slot and tabs in order to give direct placement of critical parts within the frame.
The frame will also enclose all of the electronic parts as well as the parts for power generation. A power cord will be the only needed connection to the unit and a USB will be the only needed connection to the unit for a laptop or desktop computer to connect to the printer.
THE BUILD PLATFORM

The build platform will be made from steel in order to maintain the rugged construction of the frame. The Build frame will be able to be leveled and stay leveled in order to maintain accuracy that is needed in a rapid prototyping environment. The Build table will be leveled by three springs (INFO on Springs) and consist of three layers. First, being the leveling pad which will hold the flat headed screws for the platform. Second, will consist of the PCB board that will be used to heat the build table to allow for the plastic to set correctly as it is being placed on the unit. Third will be the table itself which will act as the main platform to hold the model.
The filament being fed into the system will be completed by having the filament hang from above the unit to allow for smooth release of the filament from the roll on which it is housed. This will take away the need for the customer to have to check on the machine to make sure the filament is being fed properly. The arm will be removable in order to reduce the height for shipment.

Roll will be held on the brace by a welded frame piece and then supported by a gravity held piece on the bottom.

**THE FILAMENT APPARATUS**

Testing of the Printer will be comprised of using simple and complex models supplied by FECON, Inc. as well as models that may be found online. This will verify that the printer will function at the highest level and be able to make the most complex models accurately. The Designer will test both PLA and ABS filament to verify which is the best to use. Also the unit will be tested under supervision and unsupervised to verify that the unit can be left
overnight to make a model and not fail. This will verify that the unit can be efficient and reliable under any condition.

**SCHEDULE AND BUDGET**

Once the above engineering characteristics were agreed upon by the project advisor a schedule was then developed which can be seen in Appendix E. The design will be complete before the end of the semester. The Frame will be the first component that is designed following by the build housing, Sound housing, and Filament feeder. After the winter break most of the manufacturing will be taken place at Fecon Inc. where they have a Laser, Press Brake, Lathe, and other equipment that can complete the components necessary for the manufacture of the 3D printer. The Budget was then developed based on preliminary cost of the components. The Budget can be found in Appendix F.

**DRAWINGS**

Exploded Assembly, Weld Drawings for the frame and build platform that follow geometric tolerance guidelines can be found in Appendix G.

**COMPONENT SELECTION**

When applied standard components were selected to achieve the results that were found during the calculations. The components were selected based on those specifications and the designer’s knowledge of the product. Refer to Appendix H for drawings of some of the purchased components for the printer.
WORKS CITED


APPENDIX A - RESEARCH

Interview with VP of Engineering & Operations: Jeff Stanley of FECON, Inc. (6)3460 Grant Drive, Lebanon OH 45036  9/11/12
He has 10+ years in Engineering and design for various companies
He stated the possible benefits to having the capability of a 3D printer would be reducing the cost to prototype parts as well as the reduction in time to implement a new design in production.  As well as using the printer to show concepts of a design of new products to sales.
He had looked at various printers before that are out on the consumer market in which he felt that the high cost that is associated with the larger commercial printers was the deciding factor to not have one already.
Features he pointed out as needing were good quality parts that accurately represent what is based on the solidmodel that they put out here are FECON.

**Makergear Mosaic 3D Printer** (3)
The Mosaic 3D printer is a personal 3D printer that comes with most of the components pre assembled.  The consumers have the option of building the printer themselves or pay extra for Makergear to build it before it ships.  It is approximately 7 lbs when completely assembled and is relatively compact. Except for the power supplies.

![Figure 19](http://www.makergear.com/products/m-series-3d-printers 2/14/12)

**Mosaic Features:**
- Easy-to-assemble laser-cut wooden frame
- No soldering, no crimping
- High Quality, silky smooth linear guides and rails provide reliability, consistency and accuracy
- Incredibly smooth PTFE (non-stick) coated 4-start lead screw
- 3/8” precision-ground steel shafts with self-aligning, press-fit, precision bearings
- Fully Assembled MakerGear 1.75mm Stepper Extruder – works with ABS and PLA
- Fully Assembled RAMPS Electronics Kit
- NEMA 14 motors
- 5” x 5” x 5” build envelope (the maximum object size)
- Starter Pack of filament
- Heated Build Platform
- Misc. Extras

Has a small envelope 5” cube.  Also as the features state it has an easy to assemble frame.  I have build this before and it can be quite tedious to assemble there are a few parts that can be cumbersome to put together.  They also just allow the power supply’s to sit freely I would be good to place these in one location as it takes up room.

*Unassembled $XXX
Assembled: $XXX*
*Items are sold out online. I will update once a price returns.*

Appendix A1
BotMill Axis 3D Printer Kit (4)
The BotMill 3D printer is a personal printer. It has a larger build envelope which allows it to make parts up to 8” W x 8” L x 5” H. This in a better solution to people who may not want to scale down their parts to fit into a smaller envelope machine. It comes with everything you need to build the printer once it arrives. BotMill does offer a tech support team.

The BotMill has a larger envelope the look of the machine in the picture would lead me to believe that it is a complex machine to build. With a complicated build troubleshooting would be hard to accomplish.

Price $999.00

---

**Table: Additional Information**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>20” (610) x 14” (360) x 14” (360)</td>
</tr>
<tr>
<td>Weight</td>
<td>5.5 lbs</td>
</tr>
<tr>
<td>Build Envelope</td>
<td>8” (200) x 8” (200) x 5” (125)</td>
</tr>
<tr>
<td>Materials</td>
<td>PLA, ABS – More to come</td>
</tr>
<tr>
<td>Speed</td>
<td>0.02 inches per hour sold</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Diameter of nozzle 0.420&quot;, 0.959 min. Feature size, 0.004&quot; positioning accuracy, layer thickness 0.012&quot;</td>
</tr>
<tr>
<td>Plastic Pieces</td>
<td>Printed directly on 3D Printers; sturdy and precise. Will not break or warp, no filing or sanding required</td>
</tr>
<tr>
<td>Hardware</td>
<td>All nuts, bolts, washers and extras</td>
</tr>
<tr>
<td>Bearings</td>
<td>2 (5mm x 2mm x 7mm) = 50/44mm x 15mm x 5mm</td>
</tr>
<tr>
<td>Threaded Rods</td>
<td>M6 zinc stud - 2 x 46.0; 8 x 37.0; 4 x 29.4; 2.7 x 35.1; 1 x 41.8; 2 x 33.0</td>
</tr>
<tr>
<td>Precision Ground</td>
<td>5mm Stainless Steel alloy 303, 1&quot; x 408; 2 x 500; 2 x 405</td>
</tr>
<tr>
<td>Base</td>
<td>Made from 3mm cast acrylic</td>
</tr>
<tr>
<td>Thicks Sheets</td>
<td>X, Y, and Z</td>
</tr>
<tr>
<td>Thick Sheets</td>
<td>Table and Y spindle made of 360-0601 Aluminum</td>
</tr>
<tr>
<td>Electronics</td>
<td>State of the art electronics on one small power board</td>
</tr>
<tr>
<td>Power Supply</td>
<td>12v/24V Universal Power Supply with US/International power cord adapters</td>
</tr>
<tr>
<td>Stepper Motors</td>
<td>4 x NEMA 17</td>
</tr>
<tr>
<td>Extruder</td>
<td>Includes extruder including all plastic parts, hardware (nuts, bolts, washers...), bearings, thermistor, PTFE thermal barrier, brass nozzle, 100% resin</td>
</tr>
<tr>
<td>Tape</td>
<td>One roll of Kaption Tape and one roll of blue painters tapes</td>
</tr>
<tr>
<td>Cable Sleeve Kit</td>
<td>Package includes sleeving, tie wraps, heat shrink tubing</td>
</tr>
<tr>
<td>Tools</td>
<td>Keys, wrenches, glue and any other necessary tools</td>
</tr>
<tr>
<td>Filament</td>
<td>Free 1lb spool of plastic</td>
</tr>
</tbody>
</table>
**Dimension 1200es Series (1)**
The dimension printer series is the leader in Commercial 3D printing. It is integrated with Solidworks and other 3D modeling software. They have several different envelopes and models and are used by several large companies such as Siemens, Google, etc.

The company that I am currently working for has looked at these printers before as our Solidworks supplier (3D Vision) is a dealer for these printers. They are very good machines, but have a large price tag. Also they are rather large and can take up a lot of space in an office. If your office is small in extra room one of these systems will not be the best fit.

Price $24,900-$34,900

---

**Figure 3**

<table>
<thead>
<tr>
<th></th>
<th>Dimension 1200es 3D Print Pack</th>
<th>Dimension Elite 3D Print Pack</th>
<th>Dimension 1200es BST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build Envelope</td>
<td>254 x 254 x 305 mm (10 x 10 x 12 in)</td>
<td>203 x 203 x 305 mm (8 x 8 x 12 in)</td>
<td>254 x 254 x 305 mm (10 x 10 x 12 in)</td>
</tr>
<tr>
<td>Size and Weight</td>
<td>688 x 767 x 1143 mm (27 x 30 x 45 in)</td>
<td>666 x 914 x 1041 mm (26 x 36 x 41 in)</td>
<td>688 x 787 x 1143 mm (27 x 30 x 45 in)</td>
</tr>
<tr>
<td></td>
<td>148 kg (326 lbs)</td>
<td>136 kg (300 lbs)</td>
<td>148 kg (326 lbs)</td>
</tr>
<tr>
<td>Layer Thickness</td>
<td>254 mm (.010 in) or 330 mm (.013 in)</td>
<td>.174 mm (.007 in) or 254 mm (.010 in)</td>
<td>.254 mm (.010 in) or 330 mm (.013 in)</td>
</tr>
<tr>
<td>Modeling Material</td>
<td>ABSpix in ivory, blue, fluorescent yellow, black, red, nectarine, olive green, grey or white.</td>
<td>ABSpix in ivory, blue, fluorescent yellow, black, red, nectarine, olive green, grey or white.</td>
<td>ABSpix in ivory, blue, fluorescent yellow, black, red, nectarine, olive green, grey or white.</td>
</tr>
<tr>
<td>Support Material</td>
<td>Soluble or breakaway.</td>
<td>Soluble only.</td>
<td>Breakaway only.</td>
</tr>
<tr>
<td>Price</td>
<td>Elite: $29,900 ($22,150)*</td>
<td>Elite Print Pack: $31,900 ($20,700)*</td>
<td>1,200er BST: $24,900 ($16,500)*</td>
</tr>
</tbody>
</table>

*Note: Prices are approximate and subject to change.*


2/14/12
The ZCorp printer series offers a wide range of Commercial 3D printers for almost any application. They have several ranges that can be used in a multitude of environments from High Schools thru the largest commercial companies. They also offer printing materials to suit many needs.

The ZCorp Printers are rather interesting in the fact that they can print color while printing an entire model in the larger versions. This is quite an accomplishment to be able to act almost like an ink jet or laser printer and have the ability to use the colors in Solidworks and have the models come out with the correct color. The negative would be that it is not cost effective and you do pay for that luxury.

Price $14,900 & Up


2/14/12
**Makerbot Replicator 3D Printer** (5)

The Makerbot replicator is a personal printer that comes to the customer fully assembled. It has a dual extrusion nozzle that allows for a larger printing area as well as faster build time and allows you to use two different colors. Makerbot has a build envelope of the size of a loaf of bread.

![Figure 5](http://store.makerbot.com/replicator-404.html)

Price $1,749.00 for single extruder +$250 for dual extruder

The Makerbot has a smaller envelope that what can be best used in our company. The system itself is a good setup, but the maintenance might pose a problem and the cost of the dual extruder setup is a bit high.

*Figure 5*

**Printing**
- Build envelope: 225 x 145 x 150 millimeters or 8.9 x 5.7 x 5.9 inches
- Build volume: almost 5 liters
- Layer thickness: Choose 2.3mm with single nozzle.
- Stock nozzle diameter: 0.4 mm
- Speed: 40 mm/s
- Flow rate: approximately 24 cc/hr
- Maximum recommended extruder temperature: 230 C
- Maximum temperature for heated build platform: 120 C
- Positioning precision: 2.5 micron on Z axis, 11 micron on XY axis

**Electronics**
- MakerBot MightyBoard single-piece motherboard
- 5 axis, 1/16 micro-stepping motor control
- 4x20 LCD character display and multi-directional control pad
- Piezoelectric buzzer
- Software-controllable RGB LED lighting
- Universal Power Supply - 100-240V, 50/60Hz, 4.0A (input), and takes standard IEC cable

**Software**
- Controlled through ReplicatorG™
- Compatibility: Linux, Windows, and OSX
- Print from SD card or over USB
- Input file type: STL, .gcode

**Materials**
- Works with ABS, PLA, and other materials
- Filament diameter: 1.75 mm

**Mechanical**
- Linear ball bearings
- Precision ground 8 mm shafts
- Durable ABS injection-molded parts
- Snap-on, snap-off carriage assemblies
- Overall dimensions: 320 x 467 x 381 millimeters or 12.6 x 18.4 x 15 inches
- Shipping weight: 32 lbs
**US Patent 7373214 (7)**

This patent is for the system that turned into the 3D printer. The inventor was Kia Silverbrook and the original assignee was Silverbrook Research Pty Ltd. The system that was discussed in the patent consisted of at least one print head.

This patent is what most 3D printers are based on today and is often referenced by many when developing new technology for 3D printing.

APPENDIX B – SURVEY & RESULTS

For my Senior Design project at the University of Cincinnati I will be designing a 3D printer for my Engineering Technology degree. The survey below will help me determine the objectives of the design that will be the most important to the customer. Please use the survey to give feedback to what features you would want to see in a 3D printer if you were in the market for a 3D printer yourself.

How important is each feature to you for the design of a 3D Printer?

Please circle the appropriate answer. 1 = low importance 5 = high importance

<table>
<thead>
<tr>
<th>Feature</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>N/A</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFE</td>
<td></td>
<td></td>
<td>3(3)</td>
<td>4(3)</td>
<td>5(2)</td>
<td></td>
<td>3.9</td>
</tr>
<tr>
<td>RELIABLE</td>
<td></td>
<td></td>
<td>3</td>
<td>4(1)</td>
<td>5(7)</td>
<td></td>
<td>4.9</td>
</tr>
<tr>
<td>EASY TO USE</td>
<td></td>
<td></td>
<td>3(1)</td>
<td>4(2)</td>
<td>5(5)</td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td>EASY TO MAINTAIN</td>
<td></td>
<td></td>
<td>3(1)</td>
<td>4(5)</td>
<td>5(2)</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>QUIET</td>
<td></td>
<td></td>
<td>2(5)</td>
<td>3(1)</td>
<td>4(1)</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>COST EFFECTIVE</td>
<td></td>
<td></td>
<td>3(2)</td>
<td>4(6)</td>
<td>5</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>ACCURATE</td>
<td></td>
<td></td>
<td>3(1)</td>
<td>4(3)</td>
<td>5(4)</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>EASY TO BUILD</td>
<td></td>
<td></td>
<td>2(2)</td>
<td>3(6)</td>
<td>4</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>PLUG N’ PLAY</td>
<td></td>
<td></td>
<td>2(1)</td>
<td>3(3)</td>
<td>4(4)</td>
<td>5</td>
<td>N/A</td>
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<tr>
<td>COMPACT</td>
<td></td>
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<td>3(4)</td>
<td>4(1)</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>EFFICIENT</td>
<td></td>
<td></td>
<td>2(1)</td>
<td>3(6)</td>
<td>4(1)</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

How much would you be willing to pay for a product like this?

$1000-$2000(2)  $2000-$3000(2)  $3000-$4000(3)  $4000-$5000(1)  >$5000

Thank you for your time.
## APPENDIX C – QUALITY FUNCTION DEPLOYMENT DIAGRAM

<table>
<thead>
<tr>
<th>Garrett Ford 3D Printer 9 = Strong 3 = Moderate 1 = Weak</th>
<th>OVERALL WEIGHT (lb)</th>
<th>POWER SUPPLY (V)</th>
<th>MATERIALS</th>
<th>PRINT SET UP TIME (MIN)</th>
<th>BUILD TABLE WEIGHT (lb)</th>
<th>FILAMENT APPARATUS</th>
<th>METAL FINISH/COLOR</th>
<th>MANUFACTURABILITY</th>
<th>DAMPENING (SOUND) METHOD</th>
<th>BUILD ENVELOPE</th>
<th>LEVELING METHOD</th>
<th>Customer importance</th>
<th>Designer’s Multiplier</th>
<th>Modified Importance</th>
<th>Relative weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELIABLE</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>4.9</td>
<td>1.0</td>
<td>4.9</td>
<td>0.12</td>
<td>12%</td>
<td></td>
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<td>ACCURATE</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>4.4</td>
<td>1.0</td>
<td>4.4</td>
<td>0.11</td>
<td>11%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASY TO USE</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4.3</td>
<td>1.0</td>
<td>4.3</td>
<td>0.10</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COST EFFECTIVE</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3.8</td>
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<td>4.2</td>
<td>0.10</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASY TO MAINTAIN</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>4.1</td>
<td>1.0</td>
<td>4.1</td>
<td>0.10</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
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<td>3</td>
<td>9</td>
<td>3.9</td>
<td>1.0</td>
<td>3.9</td>
<td>0.09</td>
<td>9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLUG N’ PLAY</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td>3</td>
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APPENDIX D – PRODUCT OBJECTIVES

The product objectives are the list of features that are taken into consideration for the 3D Printer Project. I will use these as a means of proving my design was complete and followed suit with what my surveys listed as important features.

1.) SAFE
   a) Shafts of motors will have guards
   b) Exposed wires will be loomed
   c) Power supply’s will be enclosed in the unit
   d) Will calculate load rating on Motors to assure they don’t exceed the motor limit.

2.) RELIABLE
   a) Machine will print without the presence of a person
   b) Filament will feed cleanly and without binding.

3.) EASY TO USE
   a) Operator will be able to operate machine with a procedure of less than 10 steps.

4.) EASY TO MAINTAIN
   a) Bed will only need level checks annually by using basic hand tools
   b) Frame will be powder coated to prevent rust

5.) QUIET
   a) Unit will be covered to reduce noise levels.

6.) COST EFFECTIVE
   a) Prototype cost will be $2000-$3000.

7.) ACCURATE
   a) Parts created will measure out to the dimensions of the solid models ±.005.

8.) EASY TO BUILD
   a) Machine will be made of subassemblies to allow for assembly with basic hand tools.
   b) Unit Assembly time will be below 5 hours.

9.) PLUG N’ PLAY
   a) Machine will turn on by plugging in one plug and flipping a switch.
   b) Files will be maintained on a network connected to a computer/laptop.

10.) COMPACT
    a) Machine will not take up more space than a desktop printer.

11.) EFFICIENT
    a) Software will allow configuration to have any model to print in less than 10 hrs.
APPENDIX E - SCHEDULE

Garrett Ford
3D Printer

TASKS
Proof of Design Agreement to Advisor 19
Concept sketches to advisor 19
Choose Best design concept 26
3D Model - (Frame Design) 14
3D Model - (X-Y-Z Rail Component Design) 8
3D Model - (Build Platform Design) 9
3D Model - (Sound Housing Design) 16
3D Model - (Filament Feeder Design) 21
Design Analysis and final checks 14
Design Freeze 14
Detail Drawings 11
Order Long lead time component 14
Manufacture Frame 18
Oral to Faculty 18
Begin Pre Assembly/Testing 30
Paint 6
Final Assembly 1
Testing 15
Demo to advisor 29
Expo 4
Oral to Faculty 12
Report to advisor 19

Appendix E1
## APPENDIX F - BUDGET

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Appendix H3
APPENDIX H – PURCHASED COMPONENTS

M3 Screw Thread
3.5 mm Thread Depth

Guide Rail
8725K53
Sold Separately

McMASTER-CARR
PART
NUMBER
8438K4

Type 440C Stainless Steel
Threaded-Hole Rail Bearing Carriage

Appendix H4