DFMA Analysis
of the
RAPTER 3-D Printer

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Abstract

3Dreamers have designed and manufactured a portable 3D printer intended for use in the service industry that is able to operate in a service vehicle. The design of the Rapid Prototyping Transportable Extruder (RAPTER) can be broken down into three categories: mechanical, software, and electrical. The mechanical design of RAPTER consists of the structure, the gantry, the extruder, and the print platform. The design was done following Design For Manufacturing and Assembly (DFMA) methodology to optimize the product while meeting all established requirements. The structure was designed to provide durability in the rugged environment envisioned for this product. The gantry is driven by stepper motors and allows the extruder to move in the X and Y directions. The extruder is a dual-head design, allowing for structure and support material to be extruded separately. The RAPTER also contains a heated print platform to prevent the printed part from warping as it cools. The software includes both a host application that runs on a PC and firmware embedded in the printer that drives the motors and controls the thermal systems. A custom PCB was designed to interface the software system to the motors, heaters and other components that control the production of the printed part. Results yielded a robust product design showing significant competitive features in the 3D printing market.

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1.0 Introduction

3Dreamers was tasked to come up with a unique idea that would be a viable product in today's market. The team decided to explore the possibilities of 3D printing. A 3D printer is a rapid prototyping machine that creates a product using the method of additive manufacturing. It melts and then extrudes a plastic filament through a nozzle. Similar to the way a regular printer prints one line at a time on paper, a 3D printer prints one layer of an object at a time on a horizontal printing platform. Each layer bonds to the last and creates a solid part.

The result of 3Dreamers' design efforts is the Rapid Prototyping Transportable Extruder (RAPTER). By creating a portable 3D printer, 3Dreamers has developed a product to fill a need in the service industry. 3Dreamers' market research indicates that service technicians in appliance repair have a requirement to stock hundreds of parts and of these parts 40-50 percent are plastic. The RAPTER has the potential to reduce a company's inventory and eliminate the need for multiple trips to a customer when a unique or specialty part is required to solve the customer's challenge.

What makes the RAPTER unique also creates challenges. Other 3D printers on the market are used to build prototypes or are marketed for hobbyists. All are designed for and operated in a controlled environment. To make the RATPER a viable product, 3Dreamers has designed the RAPTOR to be able to fit inside a service vehicle. Since the operation environment may not be carefully controlled, the RAPTER is enclosed in order to keep contaminants out which could mar the printing. The casing also ensures that the RAPTER will function when the exterior temperature is above or below the optimal operating temperature. The printer also needs to print quickly and create accurate parts. To help maintain accuracy, a heated table is included to keep parts from cooling too quickly, which can cause the parts to warp. The printing material used by RAPTER is designed to produce durable parts and is readily available in the market. RAPTER also has a simple interface between the computer and printer for ease of use.

This document describes the RAPTER as a final product in terms of DFMA analysis and focuses on the mechanical subsystems of the RAPTER.

1.1 Product Specifications

Printer size: 18 inch X 17.75 inch X 18.5 inch
Print volume: 9 inch X 9 inch X 9.5 inch
Runs off a 12 Volt power supply
ABS with diameter of 1.75 mm
Enclosed with acrylic glass
Extruder no wider than 3.5 inches or taller than 4 inches
Host Software specifically designed
Microcontroller and PC communications through RS-232
Microcontroller controls printer functions

2.0 Concept

The concept for the RAPTER was to create a portable 3D printer to be used by service repair technicians. RAPTER is carried in the service vehicle and runs off of the vehicle's auxiliary power supply. This product is able to print plastic parts that are needed, without the service provider having to perform a return trip if he or she does not have the part. By selecting a part from a preloaded database on a service laptop, the RAPTER can quickly print the selected part. With RAPTER's large print volume it can handle large, complex parts such as a P-trap underneath a sink. RAPTER is like a portable warehouse for service repair technicians. The design of the RAPTER can be broken down into three categories: mechanical, software, and electrical.

2.1 MECHANICAL DESIGN

The mechanical design of the RAPTER printer consists of four categories: structure, gantry, print head, and print platform. The structure of the printer provides protection from its environment and allows the subsystems of the printer to be connected. The gantry is the portion of the printer that moves to control the translation of the print head. The print head can be broken into two parts: cold end and hot end. The cold end controls the feed rate of the plastic from raw filament. The hot end consists of heating elements that melt the print material, allowing the materials to extrude through the nozzle. The print platform, if used, heats the bottom surface of the printed part to reduce imperfections. It is in the mechanical design that DFMA analysis was performed, and where the paper focuses in greater detail.

2.2 SOFTWARE DESIGN

In order to print a product, the product desired needs to be modeled within Computer Aided Design (CAD) software and then imported into Computer Aided Manufacturing (CAM) software. The CAM software then determines the proper steps to perform and in what order to produce the part. The CAM software does this by producing G-code, which is code that dictates numerical coordinates that are interpreted by the microcontroller. The functions on the microcontroller control the X, Y and Z-axis motion, hot end and heated plate temperatures and feed rates for the extruders. The CAM software and functions on the microcontroller were coded specifically for the RAPTER.

2.3 ELECTRICAL DESIGN

The electrical system of the RAPTER was designed and created in order to control all the systems on the printer using the ATXmega128A3U microcontroller. The circuitry receives inputs from the computer through the RS232 serial port and then dispatches all necessary data to the corresponding motors and sensors. Data sent allows for printing of the specific 3-dimensional object selected by the user. Once one of the commands is completed, the circuit relays information back to the computer to allow for the next line of code to be sent to the RAPTER. Key components such as motor drivers, motors, and sensors are simple to replace when parts fail, allowing for fast maintenance while in the field. The RAPTER uses a custom PC Board that has ports for temperature monitoring and control, as well as axis motor and feeder motor control.

3.0 Design of Mechanical Sub-Assemblies

3.1 STRUCTURE

The frame of the 3D printer is be made of L-angle aluminum (1.5” x 1.5” x 1/8” thick). L-angle aluminum is low cost and has a high strength to weight ratio. The inherent shape allows a cube to be constructed of 12 similar pieces. Two #10-24 machine screws with nuts secure each joint. Using two screws instead of one is an area for potential redesign, addressed in section 5. The cube supports and protects the subsystems of the printer. Acrylic glass fastened on each side of the cube encases the RAPTER using machine screws. The acrylic glass protects the printer, allows the operator to see the progress of the print, and allows for more consistent control of the temperature inside the printer. The 3D printer structure can be seen in Figure 3.1: Printer Structure:

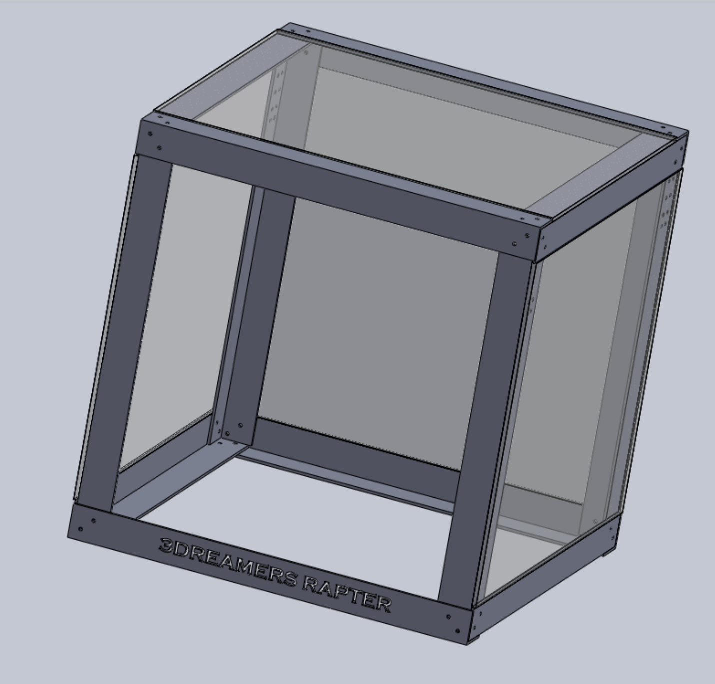


Figure 3.1: Printer Structure

3.2 GANTRY

The gantry of the 3D printer moves the print head and print platform to facilitate printing. Axes are defined to facilitate orientation: the X-axis is oriented along the front bottom edge, the Y-axis is oriented along the front-left bottom edge, and the Z-axis is oriented along the front-left vertical edge. The two main components of the gantry are the drive and linear bearings. Motors in the X and Y directions control the motion of the print head. Motors in the Z direction control the print platform motion. While printing, the print head translates in the X and Y directions until an entire layer is completed. Between each printed layer, the print platform moves in the Z direction, the distance of the desired printed layer. The gantry and axis orientation can be seen in Figure 3.2: RAPTER Gantry and Axes.

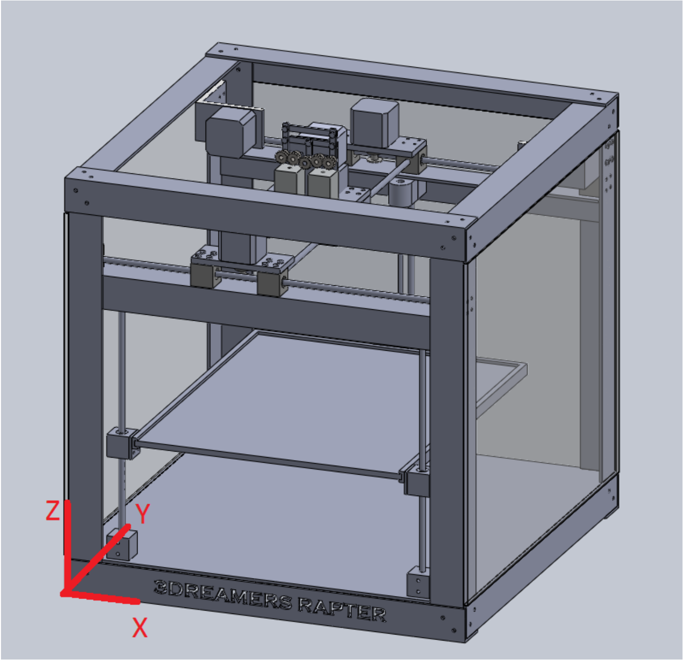


FIGURE 3.2: RAPTER GANTRY AND AXES

3.2.1 Drive

The RAPTER utilizes two different drive systems, timing belt drive systems for the gantry and an ACME screw drive system for the Z-axis. Timing belts for their low inertia, high acceleration, and high-speed capabilities drive the X and Y-axis. The Z-axis is driven by an ACME screw drive system to prevent back drive and enable for a slow translation speed.

3.2.2 Linear Bearings

To allow the drive system to translate smoothly and accurately, a linear bearing system is used. Linear bearings allow thousandths of an inch tolerance of linear motion with little added friction. Linear bearing on hardened shafts are used for the X and Y-axis movement.

Mounting holes in the linear-bearing pillow blocks, allow for rapid attachment to other parts in the printer. The bearing blocks are self-aligning to 1° and hold tolerance to 12-thousandths of an inch (ABS, 2013). Four linear-bearing pillow blocks and approximately 32 inches of shaft are required for each axis.

The linear sleeve system uses a similar hardened shaft, but the bearing sleeves do not have pre-machined mounting holes and will require a bearing block to be machined. The linear sleeve bearings allow up to 2° of shaft misalignment with shaft clearance of 1-thousandth of an inch. Mounting blocks will be manufactured to house the sleeve bearings. The CAD for the mounting block can be seen in Figure 3.3: Bearing Sleeve Mounting Block.

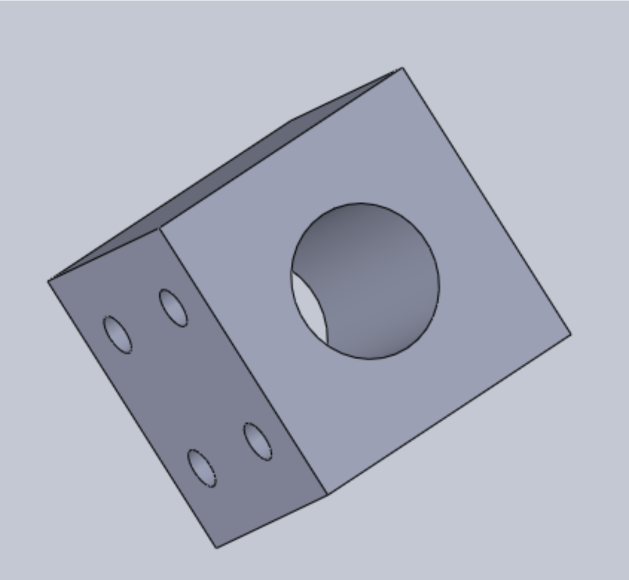


FIGURE 3.3: BEARING SLEEVE MOUNTING BLOCK

3.2.3 Motors

Stepper motors allow for a precise rotation and through the drive system, equate to a precise linear translation that can be accurately controlled.
The RAPTER uses a total of seven stepper motors. Four are used to drive the X and Y motions of the gantry. The reason for using two stepper motors for each direction is to increase the torque on the drive system since when the motors are micro stepped there is a torque loss. To prevent binding in the Z direction, there are 3 ACME screws and 3 stepper motors to control the motion of the Z-axis.

3.3 PRINT AND SUPPORT MATERIAL

3.3.1 Print material

The print filament selected for the RAPTER is Acrylonitrile Butadiene Styrene (ABS) plastic. Utilizing ABS plastic allows the RAPTER to print more durable components.

3.3.2 Support Material

The RAPTER uses Polyvinyl alcohol (PVA) for the support material when printing parts with overhangs. PVA is water-soluble, which allows for support material to be safely dissolved within a utility vehicle.

3.4 EXTRUDER

The combined cold end and hot end allows for the RAPTER to have both an energy efficient extruder as well as a less intrusive gantry. A less intrusive gantry allows for larger objects to be printed.

3.4.1 Cold End

A basic representation of the independently driven cold end can be seen in Figure 3.4: Independent Cold End Mechanism.

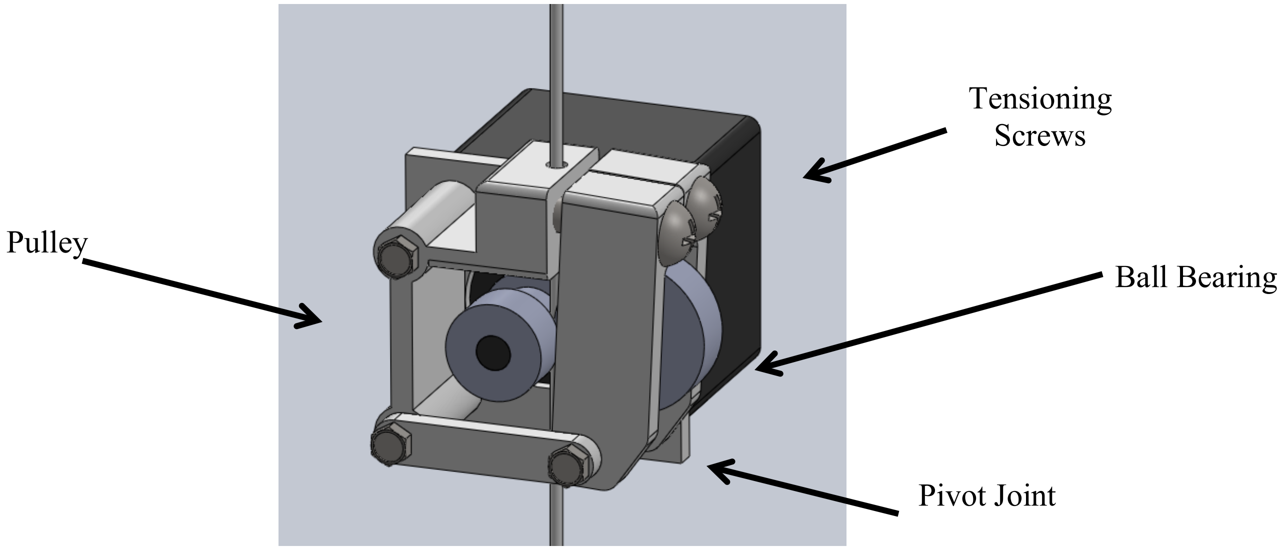


FIGURE 3.4: INDEPENDENT COLD END MECHANISM

The filament will be fed in between the pulley and ball bearing. The pulley is in a fixed position, attached to the shaft of the stepper motor and the ball bearing is adjustable. The mount for the ball bearing includes a pivot joint and tensioning screws. By tightening the tensioning screws, the mount's angle will change, moving the ball bearing closer to the pulley and filament. This will in turn put a force onto the filament. With this force, the pulley will feed the filament to the hot end.

To mount the independently driven cold end onto the RAPTER, the following chassis was designed. Figure 3.5: Assembled Cold End shows the chassis as well as two of the independently driven cold ends mounted.

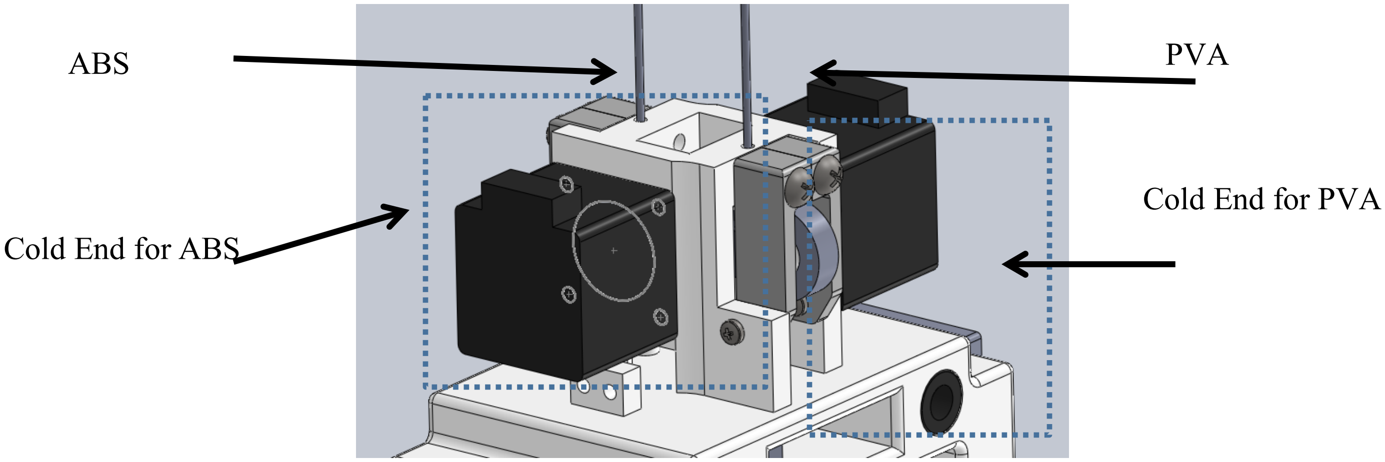


FIGURE 3.5: ASSEMBLED COLD END

3.4.2 Hot End

The hot block is 1.25 inches long by 1.00 inch wide by 0.50 inches thick. This allows the heater cartridge and nozzle to be incorporated in an efficient block. The block is covered with Kevlar insulation with the reflective side facing the hot block to limit radiation absorption by the cold end. To help retain energy in the heating block, Teflon and Kapton tape are used to wrap the block. To dispose of excess energy away from the hot block and also ensure steady phase change of the filament, a heater barrel and PFTE tubing are used to guide filament from the cold end to the hot end. The PFTE tubing guides the filament to the opening of the nozzle and makes the path from the roll to the hot end as frictionless as possible. The heater barrel locks the PFTE tubing in position to insure smooth feeding. It also radiates energy away from the hot end to fins that are attached to the barrel, which gives the filament a steadier temperature change for stable flow. The hot end can be seen attached to the RAPTER in Figure 3.6: Hot End.

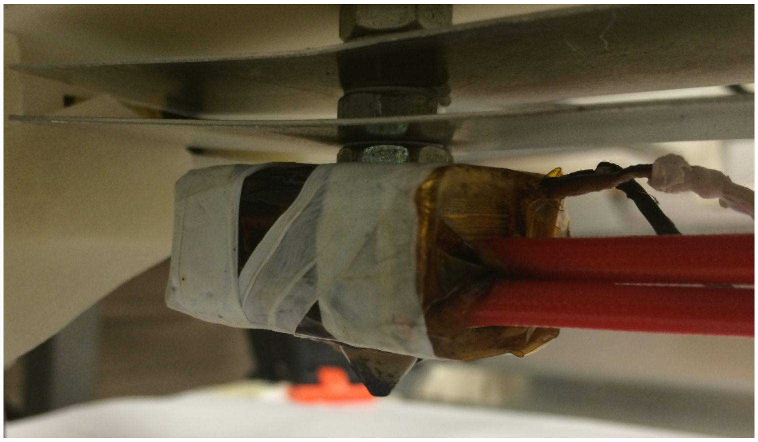


FIGURE 3.6: HOT END

The temperature probe is a thermistor inserted into the block halfway between the heater cartridge and the outer edge and halfway between the top of the block and the bottom. Having the probe in this position allows for the code to be set and left alone unless the filament changes. It also ensures accurate and precise temperature readings of the block, which means that the temperature of the nozzle can be reliably inferred.

3.5 HEATED PLATE

The plate designed by 3Dreamers consists of a 10 in by 10 in by 1/16 in thick plate of aluminum, heated by nine 20-ohm resistors wired in parallel. The topside of the plate can be seen on the following page in Figure 3.7: Heated Plate Topside.

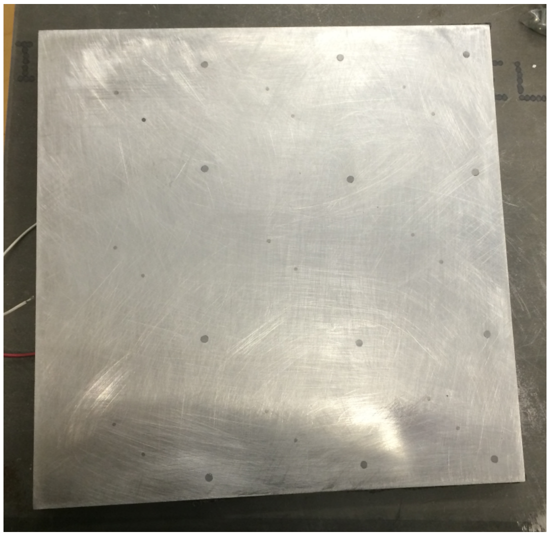


Figure 3.7: Heated Plate Topside

The topside of the final heated plate design was filed and sanded smooth to prevent any potential deformities during printing and cooling. The plate was also placed face down on a specialized tabletop that is level to 1/1000th of an inch and produced negligible rocking corner to corner.

To limit the plate's energy loss, the plate was insulated on its backside with high temperature insulation. The surface of the plate is where the energy needs to be focused for the plate to work. Using nine resistors reduced the surface area between the heating elements, which in turn limited the potential for hot and cold spots on the plate's surface, which can negatively affect or even ruin printed products. The nine resistors and insulation can be seen in Figure 3.8: Heated Plate Underside.

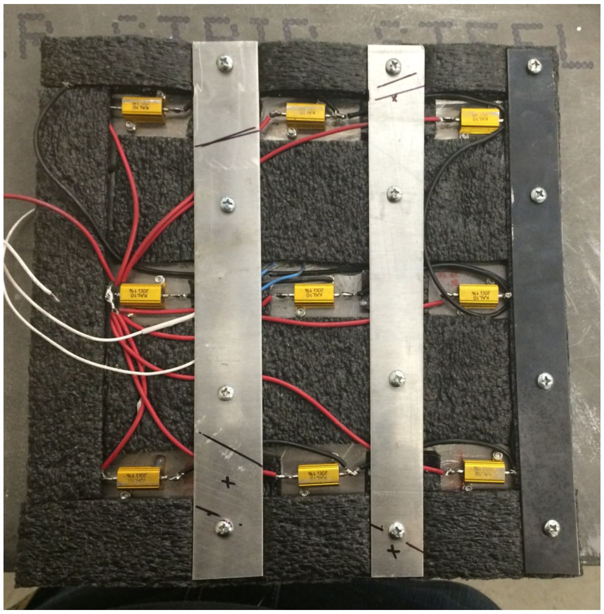


Figure 3.8: Heated Plate Underside

The metal bracing running up and down the plate was attached to prevent warping caused by the plate heating and cooling, or potentially causing a defect in the material. The braces also double as an area where bolts can be threaded to hold the plate in place inside the printer during extrusion and transport.

4.0 Power Budget

4.1 HOT END POWER CONSUMPTION

Starting with the hot end, the total power consumption for both heater blocks after design modifications came out to be 35.44 W and a current consumption of 2.95 A. This value is the combination of radiation loss, convection loss and conduction loss, which is the energy required to melt ABS plastic. This energy requirement will be satisfied with a 40 W commercial, off-the-shelf (COTS) heater cartridge rated for a 12 V system, which is inserted into each heater block for a total of 80 W of heating energy for the hot end and 6.7 A of current. The energy draw for the hot end, consisting of both heating blocks during the starting procedures, is roughly 13,700 J of energy per unit area. This energy draw is starting from an assumed ambient temperature of an average room temperature. The equations and assumptions used to calculate the current, power and energy draw can be examined further in 8.0 Appendix I: Energy Calculations. The hot end power consumption is shown in Table 4.2: Power Consumption for Hot End.

TABLE 4.2: POWER CONSUMPTION FOR HOT END

Power (W	Current (A)	Voltage (V)
80	6.7	12

4.2 HEATED PLATE POWER CONSUMPTION

The next subsection to be examined is the heated plate. The heated plate power and current draw is 53 W and 4.5 A. Heating the plate from room temperature to operating temperature is approximately 9,400 J of energy per unit area of the plate. Further inquiry into the mathematics can be observed in 8.0 Appendix I: Energy Calculations. The energy consumption for the heated plate is shown in Table 4.3: Power Consumption for the Heated Plate.

TABLE 4.3: POWER CONSUMPTION FOR THE HEATED PLATE

Power (W)	Current (A)	Voltage (V)
53	4.5	12

4.3 OTHER COMPONENTS POWER CONSUMPTION

Using the product ratings for the purchased motors changed the total power draw for the motors to 72 W. After the motors, only a small percentage of the overall power consumption has not been examined.

The last section is the electronics section. Knowing which fans were set to be used, but not knowing the microcontrollers precisely, or the energy losses expected from electrical components manufactured by the 3Dreamers, has made the total power consumption for the electronics only partly known. The power draw for all three of the fans is 0.70 W; current draw is 0.58 A, and is lumped together with the other electronics. The power consumption for miscellaneous components is presented in Table 4.4: Power Consumption for Miscellaneous Components.

TABLE 4.4: POWER CONSUMPTION FOR MISCELLANEOUS COMPONENTS

Subsystem	Power (W)	Current (A)	Voltage (V)
Motors	72	6	12
Electronics	18	1.5	12

4.4 TOTAL POWER CONSUMPTION

Table 4.5: Power Break Down shows the rated voltage, current required and power required for each of the sections mentioned above.

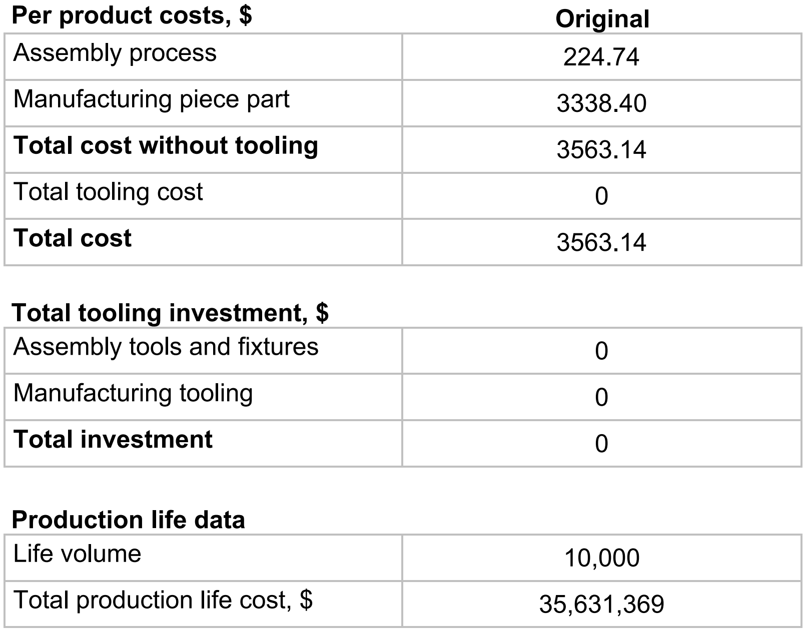
TABLE 4.5: POWER BREAK DOWN

Subsystem	Supply Voltage (V)	Power (W)	Current (A)
Hot End	12	80	6.7
Heated Plate	12	53	4.5
Motors	12	72	6
Electronics	12	18	1.5
Total	**12**	**223.5**	**18.7**

The total energy requirement for the RAPTER from the power break down above is 223.5 W. To ensure the RAPTER is protected from any power surges from the battery or short circuits in the vehicle, a 25 A fuse is wired in series with the main power cable running to the RAPTER. The wire used for the main cord is a #8 gauge wire. The majority of the energy draw for the RAPTER during the start-up sequence is the heated plate and the hot end. Combining these sections together gives total energy consumption of just over 23 KJ or over a 5-minute start up sequence, a power consumption of 77 W.

5.0 DFMA

The RAPTER has further analyzed utilizing Boothroyd Dewhurst DFMX software for further product optimization. The printer was broken down into sections such as the gantry, hot end, cold end, heated plate, structure, electronics and frame. Each piece of hardware was categorized by what subsystem it fell under and listed within the software. The software examined the financial cost, production and assembly cost of each part. The software then calculated which items listed would be best removed based upon user defined information. Figure 5.1: Analysis Totals for DFMA: presents the total cost break down for the parts, assembly processes and tooling costs.



Per product costs, $	**Original**
Assembly process	224.74
Manufacturing piece part	3338.40
Total cost without tooling	3563.14
Total tooling cost	0
Total cost	3563.14

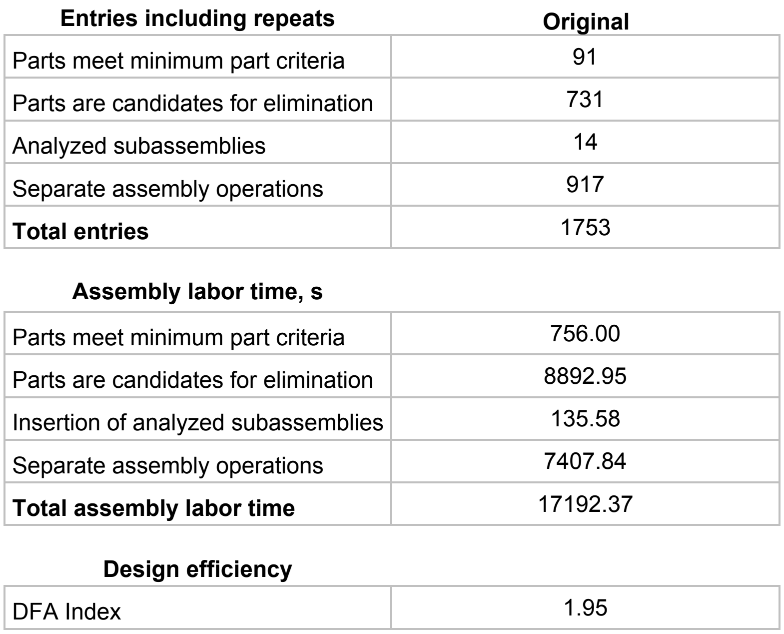
Total tooling investment, $	
Assembly tools and fixtures	0
Manufacturing tooling	0
Total investment	0

Production life data	
Life volume	10,000
Total production life cost, $	35,631,369

FIGURE 5.1: ANALYSIS TOTALS FOR DFMA

Since the RAPTER is a prototype version, the tooling costs weren't fully known and couldn't be reasonably estimated for the analysis. The *total parts cost* for the printer was 93.7 percent of the entire cost for the RAPTER, which came to $3,338.40. The total cost for the *assembly processes* came to $224.74. The total cost of the entire printer was $3,563.14 per unit.

From Analysis Totals for DFMA, the Analysis Totals for DFA are examined next. The analysis can be seen broken down into *entries*, *labor time* and the calculated design efficiency, which is presented on the following page in Figure 5.2: Analysis Totals for DFA:



Entries including repeats	Original
Parts meet minimum part criteria	91
Parts are candidates for elimination	731
Analyzed subassemblies	14
Separate assembly operations	917
Total entries	1753

Assembly labor time, s

Parts meet minimum part criteria	756.00
Parts are candidates for elimination	8892.95
Insertion of analyzed subassemblies	135.58
Separate assembly operations	7407.84
Total assembly labor time	17192.37

Design efficiency

DFA Index	1.95

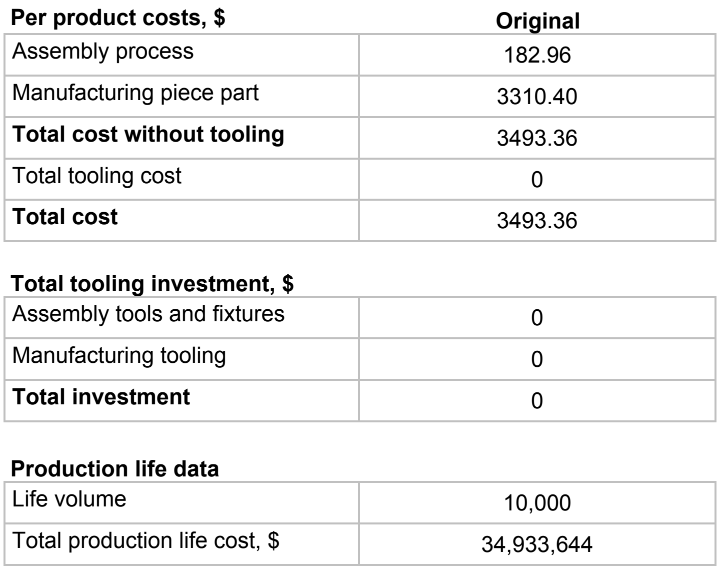
Figure 5.2: Analysis Totals for DFA

The software determined 731 parts were eligible for elimination or redesign, with 14 *subassemblies* and 917 *separate assembly operations*, culminating in 1,753 total entries.

The assembly time is broken down into *minimum part criteria*, *candidates for elimination*, *analyzed subassemblies*, and *separate assembly operations*. There were 756.00 seconds allocated to parts that met the *minimum part criteria*, 8,892.95 seconds required for parts that fit as *candidates for elimination*, 135.58 seconds used for the *insertion of analyzed subassemblies*, and 7,407.84 seconds for *separate assembly operations*. The total time to produce a single RAPTER was calculated to be 17,192.37 seconds, or 4.78 hours.

After calculating the total assembly time and number of components and subassemblies the DFA Index for design efficiency was calculated to be 1.95. Obtaining a DFA Index above 1.00 is typically considered to be a good index value, depending on the size and complexity of the system being analyzed. The RAPTER received a decent score before any proposed redesigns were applied.

The total cost break down after applicable redesigns were applied and can seen on the following page in Figure 5.3: Redesign Analysis Totals:



Per product costs, $	**Original**
Assembly process	182.96
Manufacturing piece part	3310.40
Total cost without tooling	3493.36
Total tooling cost	0
Total cost	3493.36

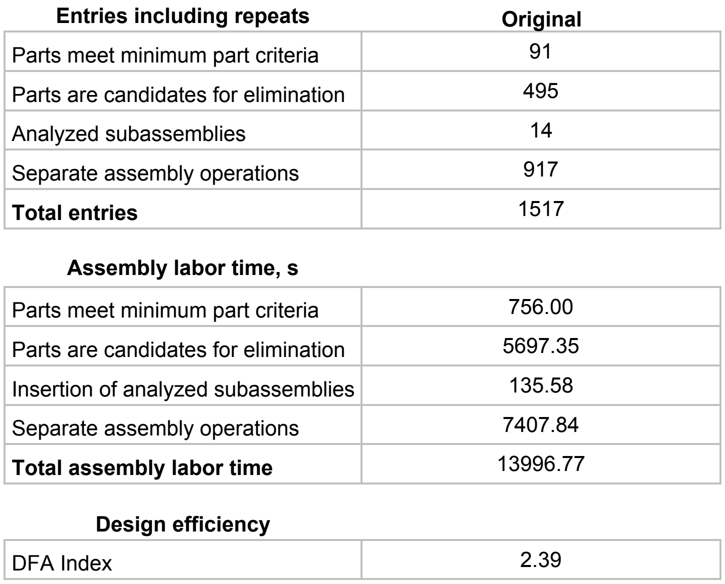
Total tooling investment, $	
Assembly tools and fixtures	0
Manufacturing tooling	0
Total investment	0

Production life data	
Life volume	10,000
Total production life cost, $	34,933,644

FIGURE 5.3: REDESIGN ANALYSIS TOTALS

The assembly process cost was reduced down to $182.96, a 18.6 percent reduction from the original. The *manufacturing piece part* section costs came to $3,310.40, a 0.84 percent reduction. The resulting total for each RAPTER unit dropped to $3,493.36, which is an overall reduction of 1.96 percent.

The redesign's modifications to the total number of entries as well as total labor time are seen in Figure 5.4: Redesign DFA Analysis Totals:



Entries including repeats	**Original**
Parts meet minimum part criteria	91
Parts are candidates for elimination	495
Analyzed subassemblies	14
Separate assembly operations	917
Total entries	1517

Assembly labor time, s	
Parts meet minimum part criteria	756.00
Parts are candidates for elimination	5697.35
Insertion of analyzed subassemblies	135.58
Separate assembly operations	7407.84
Total assembly labor time	13996.77

Design efficiency	
DFA Index	2.39

FIGURE 5.4: REDESIGN DFA ANALYSIS TOTALS

The software determined 495 parts were eligible for elimination or redesign, with 14 *subassemblies* and 917 *separate assembly operations*; culminating in 1,517 total entries, a 13.5 percent reduction.

The assembly time was broken down into *minimum part criteria*, *candidates for elimination*, *analyzed subassemblies*, and *separate assembly operations*. There were 756.00 seconds allocated to parts that met the *minimum part criteria*. 5,697.35 seconds required for parts that fit as *candidates for elimination*. 135.58 seconds used for the insertion of *analyzed subassemblies*, and 7,407.84 seconds for *separate assembly operations*. The total time to produce one RAPTER was calculated to be 13,996.77 seconds or 3.89 hours, a 18.6 percent reduction in production time over the original.

After calculating the total assembly time and number of components and subassemblies, the DFA Index for design efficiency was calculated to be 2.39; an improvement of 18.4 percent. Since the RAPTER was initially designed with efficiency and budget in mind, the redesign only eliminated redundant screws in the frame. Many of the components that the DFMX software suggested could be removed due to price and complexity were integral parts of the RAPTER, which meant they couldn't be eliminated. Motors have been optimized in the initial design by the criteria to be energy efficient. The cold end, bearing and mounting blocks were consistently suggested as redesign criteria because of their cost and complexity. Since these parts are printed from a 3D printer to save labor and material costs, the only foreseeable way to reduce the cost for these parts would be to reduce their manufacturing costs. The majority of the RAPTER's costs are only reducible if some of the design criteria for the RAPTER are ignored, such as durability and accuracy. The other way some prices can be reduced, specifically the printed parts and the PCB, is to find a supplier to purchase the components from at a lower cost, or invest in a 3D printer and etching equipment to produce these components in house.

6.0 Conclusion

The RAPTER is a robust 3D printer with the capability of operating in atypical environments for additive manufacturing and is also energy efficient, drawing under 20 A of current on a 12 V system. The design of the mechanical and electrical components for the RAPTER allow for ease of maintenance and replacement when parts wear out. The software and PCB were designed specifically for the RAPTER. The extruder incorporated into the RAPTER was designed to minimize the space consumed, while maximizing the print volume of the RAPTER. The printer is 18 inches by 17.75 inches by 18.5 inches, with a print volume of 9 inches by 9 inches by 9.5 inches. The RAPTER's initial design criteria and ultimate goal of being a portable 3D printer, led to a final product with strong market potential, but limited DFMX redesign potential. With the applied recommendations from the DFMX software applied, an 18.4% cost reduction was seen, yielding an individual unit cost of $3500.

7.0 Citation

Duke, M., Ertl, S., Islas, A., Rictor, A., Rivers, J., Smith (Vieira), M. & Wallace, K. (2014, April 25). *RAPID PROTOTYPING TRANSPORTABLE EXTRUDER (RAPTER)*. Paper presented at the Spring 2014 Embry-Riddle Aeronautical University Senior Capstone Symposium, Prescott, AZ.

8.0 Appendix: Energy Calculations

The energy requirements for the RAPTER are based off of the equations for radiation energy loss, convection energy loss, conduction energy loss, the power ratings for the individual components and energy required to reach a given temperature differential.

Radiation energy loss is the least amount of energy loss. The equation for radiation loss is Equation 1. The variables that need to be defined for Equation 1 are surface area, A, surface constant, ε, ambient temperature in absolute value, T_∞ and last is the desired temperature in absolute value, T. The only value that is a constant is the Boltzmann's constant, σ.

$$q = \sigma\varepsilon A(T^4 - T_\infty^4) \qquad \text{Equation 1}$$

For the hot end, surface area is equal to 2.8E-3 m^2. The Boltzmann's constant is 5.67E-08 W/m^2K^2. The surface coefficient is 0.07 for finished aluminum. The ambient temperature is presumed to be 20 ℃ and the operating temperature is 250 ℃. Inserting these values into Equation 1 yields a radiation energy loss of 0.78 W.

For the heated plate, surface area is equal to 0.065 m^2. The Boltzmann's constant is 5.67E-08 W/m^2K^2. The surface coefficient is 0.07 for finished aluminum. The ambient temperature is presumed to be 20 ℃ and the operating temperature is 90 ℃. From these values in Equation 1 the radiation loss is 2.04 W.

Conduction energy loss is the next energy loss to be calculated. The equation for conduction energy loss is Equation 2. The variables that need to be defined are mass, m, the conduction coefficient, c, and temperature differential, ΔT.

$$q = mc\Delta T \qquad \text{Equation 2}$$

For the hot end, the conduction energy loss is the same as the energy draw to melt the filament. From this assumption, the mass used is the mass of filament being pushed through the hot end. This is calculated from the density per volume of filament, 1.93 g/cc and the thermal coefficient 2.13 J/gcc. Conduction coefficient for ABS plastic is 0.128 W/mk. Last that is needed is the temperature differential which is presumed to be 230 ℃, which is the difference between the ambient temperature of 20 ℃ and the extrusion temperature of 250 ℃. From these values, the conduction energy loss calculated in Equation 2 is 10.06 W.

Convection energy loss is the last of the energy losses to be calculated. The equation for convection loss is Equation 3. The variables that need to be defined for convection energy loss are the convection coefficient, h. Surface area exposed to the convection current, A and the temperature differential, ΔT.

$$q = hA\Delta T \qquad \text{Equation 3}$$

For the hot end, surface area is equal to 2.8E-3 m^2. The temperature differential is presumed to be 230 ℃ again. The last value that needs to be calculated is the convection coefficient, h. This is calculated from Equation 4, which is only dependent on the velocity of the current passing over the surface area. The velocity used was the desired extrusion rate of 200 in/min or 0.08 m/s. Since the gantry has to move back and forth across the printer at a speed that can keep pace with the desired extrusion rate. From Equation 4 the convection coefficient, h is 10.44 W/m^2 ℃.

$$h = 10.45 - v + 10v^{0.5} \qquad \text{Equation 4}$$

The resulting convection energy loss from Equation 3 is then calculated to be 6.89 W.

For the heated plate, surface area is equal to 0.13 m^2. The temperature differential is presumed to be 37.7 ℃, which is the difference between the ambient temperature of 20 ℃ and the surface temperature of 57.7 ℃. The last value that needs to be calculated is the convection coefficient, h. This is calculated from Equation 4, which is only dependent on the velocity of the current passing over the surface area. The velocity used was of 12(in/min) or 0.005 m/s. Since the heated plate is mainly stationary and there are no fans blowing across the surface, a slower velocity sufficed. From Equation 4 the convection coefficient, h is 10.45 W/m^2 ℃. The resulting convection energy loss from Equation 3 is 51.45 W.

For all of the purchased electrical components and motors, if the power rating is not presented in the data sheets but the rated voltage and rated currents are present. The expected power draw is calculated from Equation 5 using the voltage and current.

$$P = VI \qquad \text{Equation 5}$$

The initial energy requirements were calculated from Equation 6. The constants for the initial energy are the thermal coefficient, c, gamma, which is mass per volume, temperature differential, ΔT and volume, V.

$$Q = c\gamma V \Delta T \qquad \text{Equation 6}$$

For the hot end, the thermal coefficient is 896 J/kg ℃. Gamma is the density, which is 2700 kg/m^3. V is the volume, which is 1.23E-05 m^3 and last is the temperature differential of 230 ℃. The initial energy required by the hot end from Equation 6 is 13676.98 J.

For the heated plate, the initial energy calculation uses the same thermal coefficient and density as the hot end; the volume is 1.02E-04 m^3 and last the temperature differential is 37.7 ℃. Changing the volume and temperature differential in Equation 6 gives an initial energy requirement of 9341.02 J.