Design for Manufacturing, Reliability, and Economics

Team 19
CNT Reinforced Ceramics 3D Printer

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ABSTRACT

The project described along this report involves the modification of an already existing 3D printer that is be capable of extruding a novel material developed by the team sponsor, Dr. Cheryl Xu. The printing of this material requires an extrusion head able to eject a paste like material, and a curing system capable of solidifying the paste like precursor in a fair period of time. Since the properties of the material that Team 19 is intending to print differ from those of the plastic materials, the team had to completely modify the extrusion head of the purchased printer, and additionally the team had to add a curing system into the 3D printer design.

In addition, this report includes a design for reliability analysis that contains a deep examination of the possible causes of failure related to this project. An FMEA analysis was performed, and the results showed relatively low risk priority numbers, except for the coding step that will be further explained in this report. Finally, a design for economics analysis is performed to see the total cost of this project and determine how competitive will it be on the market. Nevertheless, since there is no comparable existing 3D printer, the team concluded that this is highly competitive.

ACKNOWLEDGEMENTS

Much of what has been accomplished this semester would not have been possible without the knowledge and experience graciously shared with Team 19 from numerous professors and College of Engineering staff. Team 19 would like to thank each and every one of these individuals for their contributions to the team's progress. First and foremost, the team's very own sponsor

Dr. Cheryl Xu has been the strongest support of all. She has opened the Ceramic Composites Manufacturing Lab operating under the Mechanical Engineering Department to Team 19 to use for their senior design project, and has given them the opportunity to incorporate additive manufacturing with a senior design group.

Dr Wei Guo has been very helpful and explained theoretical aspects to the team whenever they needed. He was ready to provide input at any given time no matter what the subject might be and steered the team in the right direction.

Dr. Jinshan Yang, one of Dr. Xu's graduate students, was very helpful to the team and helped identify the materials characteristics and gave insight in understanding how the materials are projected to behave when mixed. He also supplied help in the lab for preparation of the experiments.

Dr. Yong Huang from the University of Florida has provided information taken from his own experiences from 3D printing to the team's efforts. With so many possible methods of extrusion available and with such a unique material to extrude, the issue of how to best extrude the ceramic polymer composite was resolved in a discussion.

Jonathan Cloos and Cindy Stewart from the Mechanical Engineering department have been extremely helpful in financial matters. Both of them answered the team's emails in a timely manner, and ordered the components once they were required without any type of delays.

Department of Mechanical and Department of Industrial and Manufacturing also helped the team in acquiring information about the timeline and the deliverables. Departments also presented many knowledgeable staff and faculty ready to assist all senior design teams.

1. Introduction

This report provides detailed information regarding design for manufacturing, design for reliability, and design for economics for Team 19's project. These three analyses are considered extremely important for the development of a project, mainly because the good practice of them will determine the success of the project. First of all, a brief background and review of the project will be explained in depth in order to guide the reader through the objective of this project, and to show the different directions that this project has taken. The following sections will explain and demonstrate how this project was designed and assembled, taking into consideration the cost of each of the components, and how reliable the process is with the implementation of the current components.

The concept of Design for Manufacturing (DFM) refers to the process of planning and designing a process or a product that is easily and economically manufactured [1]. This concept will be vastly applied throughout this report to determine how good the design is implemented for the CNT reinforced polymer 3D printer. In order to determine if Team 19's project follows the DFM principle, some parameters must be analyzed. These parameters include the total number of parts, the use of multifunctional parts, ease of assembly, minimization of handling, among others.

Additionally, a good project must include a reliability assessment in order to determine how the product will perform with time. This is one of the most important analyses, because it studies the different potential failures that a project might face. If these problems can be avoided by changing something on the design, the modification must be made during the design phase to avoid extra costs in the future [2]. Moreover, an appropriate reliability study will warranty customer satisfaction, which is one of the goals of this project.

Design for manufacturability, and design for reliability goes hand and hand with the design for economics, which will also be analyzed along this report. A breakdown of the component's costs will show if this project is able to compete with other products on the market, and if the team was able to fulfill the sponsor's budget constraint.

2. Background and Literature Review

Conventional ceramics has been present in the engineering world since many years ago, and they have been used for different purposes due to their numerous advantages including heat resistance, and relatively cheap production cost. However, it also has a relatively low modulus of elasticity as well as a low tensile strength, compared to other types of materials such as metals, and plastics. As a result, material developers felt the necessity of developing an improved ceramics material, which they called Polymer-Derived Ceramics (PDC).

Polymer derived ceramics are known to be corrosive, abrasive, oxidation, and creep resistant. Additionally, when mixed with CNTs, their thermal and electrical properties are highly increased as well as its mechanical properties, which can be compared to those of graphite or Al_2O_3 [3].

The problem with this kind of improved material is that the current production process, produces too much waste, which turns it into an unfeasible manufacturing material due to the high expenses that the waste of material produces. Therefore, more viable manufacturing technologies are being researched for the production of this type of material. Additive manufacturing is one of those production methods.

The reason why additive manufacturing is being considered is, it does not produce any waste of material; it prints the specified shape without further need of machining. Currently, there is not a publicly known additive manufacturing technology able to print polymer derived ceramic that is reinforced with CNT's, thus Team 19 will be modifying an existing 3D printer that follows the fused deposition modeling (FDM) principle, into a 3D printer able to follow a liquid deposition modeling (LDM) technique. In order to do that adjustment, the team will have to modify the extrusion head together with the printer profile, and add a curing system to solidify each layer of material before extruding the next.

The following sections explain the designs selected for this adjustment, and the assembly process required for the completion of the transformation. In addition, a reliability analysis, and an economic analysis were develop to determine how will the reinforced ceramics 3D printer perform, and how commercially competitive will it be in terms of costs.

3. Design for Manufacturing

Since this project involves the use of an already existing 3D printer, the assembly process does not include many steps. Team 19's Reinforced Ceramics 3D Printer is mainly conformed by the printer itself, the extrusion head, the curing system, and the control and data gathering devices. The following paragraphs will be explaining in depth the assembly process, and specifications for each of the components mentioned before.

3.1. 3D Printer

The 3D printer that Team 19 chose to use is called the Lulzbot TAZ 4. This printer offers various features that fit perfectly to the needs of the project. Its design offers enough clearance around the print head, it has its own LCD screen, which allows the user to control the printer and monitor the printing process; and it is fairly portable. It has a weight of 24.25 pounds, and overall dimensions of 680mm x 520mm x 515 mm (26.8in x 20.5in x 20.3in). Originally, it followed a fused deposition modeling (FDM) mechanism that allowed the user to print different thermoplastic materials, including ABS, PLA, HIPS, and PVA. Since this is a commercially available device, the team together with the sponsor, decided to order it semi-assembled. As a result, the device itself did not require any tooling process in order to put it together.

3.2. Extrusion Head

The different parts that conform this component include the skeleton of a syringe pump, a 20 mL syringe, a stepper motor, a 22 gauge dispensing blunt tip needle, and ABS plastic 3D printed pieces that were used to attach the whole design into the printer. The 3D printed pieces include one pinion attached to the stepper motor, one gear attached to a threaded rod of the syringe pump skeleton, and brackets. The design the team decided to implement for the extruder head is compatible with the design of the extruder head that came with the purchased 3D printer; this means that the extruder heads can be easily switched from one to the other depending on which material the user wants to print at a certain time, plastic or reinforced ceramics. A detailed view of this component is shown in Appendix A.

3.3. Curing System

The curing system purchased for the 3D printer was called "Melody Susie." This curing system is the same types of curing method used at nail salons to cure the nail polish. The configuration contains four, nine-Watt bulbs that produces a total of 36 Watts. The rated voltage ranges from 110 to 120 Volts, and the rated current ranges from 0.2 to 0.35 Amperes. The dimensions of the system was (260mm x 230mm x 110mm). The curing system had to be re-engineered to attach it onto the extruder head. The team took apart the chassis to the system and kept the UV bulbs, bulb attachments, and the circuit board to power the system. Rewiring of the UV attachments to the circuit board was done in order to achieve additional length, so that the circuit board can sit off to the side while printing is in process. The reconfigured system can be seen in Appendix A.

3.4. Control and Data Gathering Devices

The control devices that Team 19 is currently using includes an infrared thermometer, a camera, and a dedicated computer for the 3-D printer. This devices allow the user to record some data from each of the printing works, including videos, a closer look of the extrusion process, a closer look of the curing process, the temperature at which the printing process was held, among others.

1. Dedicated Computer

   This is the only device from the control devices group, which is connected to the 3D printer. It is connected through a USB cable, and it allows the user to use the Slic3r software in a more comfortable way. Additionally, the recorded data can be stored in this computer for future usage.

2. Camera

   The camera that the team decided to purchase is a Logitech HD Pro Webcam C920. This component is directly attached to the computer, and even though it is not attached to the printer itself, it represents an important asset for the team's project, because it allows recording the different print jobs in order to further determine if everything is working well, or if the printer requires modification of a certain component, or maintenance. In order to use this component, the team decided to purchase an Arkon C-clamp camera mount to support the camera. This mount include advantageous features such as its 12" flexible gooseneck and a swivel ball that provide an ideal positioning of the camera. Refer to Appendices B and C to see both the camera and the camera mount with their features.

3. Thermometer

   The temperature sensor that the team decided to purchase is an Etekcity 630 digital dual laser with infrared thermometer laser sight. This device is not connected to the printer, or the computer; it is an individual device that requires the presence of the printer operator to be used. Refer to Appendix D for more details about this device.

Since the design of this project involves the use of a novel material mixture, a series of steps were needed before the design phase. In the first place, the team spent a fair amount of time researching, looking for appropriate components, and trying to understand how the polymer mixture behaves. It is important to mention that the team's project scope changed multiple times, as a result, the time to accomplish the final project was used to work on other issues that are no longer part of the team's project. Taking into account research, material and component purchase, experimentations, design, and assembly, the project took approximately seven month to be completed. The assembly took approximately two months, which was the estimated time. Nevertheless, there were some delays with the experimentation phase, because the team was not getting the expected results.

Even though Team 19's project involves the use of an already existing 3D printer, a lot of components and pieces were used to modify the extruder head, and to add a curing system to the printer. Since the project requires a high level of accuracy and precision, the team consider that all of these components are necessary for precision, and that complexity is more appropriate for this kind of project.

4. Design for Reliability

This section of the report intends to forecast the performance of the team's project over certain periods of time, and to address specific possible failures that may occur with the passing of the time. The system's quality and reliability were a persistent focus during the design process. In order to address reliability issues, the team prepared several experiments before the assembly process. Additionally, designs were constantly reviewed, and a FMEA analysis was performed to determine possible failures together with their cause and solution.

4.1. Performance Measurements

According to different customer reviews, the TAZ 4 3D printer has an approximate reliability of 85%. Assuming that its reliability will decrease by 10% when all the modifications are implemented, the reliability of the modified prototype would be approximately 76.5%.
Using Equation 1, and Equation 2, Team 19 was able to forecast the performance of the 3D printer prototype when used once, and when used for a longer period of time.

$$R(t) = e^{-\lambda t} \tag{1}$$

$$MTBF = \frac{1}{\lambda} \tag{2}$$

Equation 1 refers to the probability that the system experiences no failures during a certain period of time, where λ is the rate of failure and t is a specific period of time. Likewise, Equation 2 describes the mean time before failure (MTBF), which refers to the time passed before a system fails under constant conditions.

Assuming that a standard print job will take approximately five hours to be completed, the failure rate would be 0.0536 failures per hour, or approximately five failures every hundred hours. Taking into consideration the previous value, the mean time before failure would be approximately 18.66 hours. Refer to Appendix E to see the complete calculations.

These calculations indicate that after approximately 4 print jobs, the 3D printer will require immediate maintenance before proceeding to the next printed piece. As a result, the printer should be able to perform well by the 100th time used, however, it will require pertinent maintenance sessions between print jobs.

4.2. Failure Mode and Effects Analysis

The FMEA analysis is shown in Table 1. It shows the potential failures of this project based on experience with the components independently, and based on common logic.

Table 1: Failure Mode and Effects Analysis

Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN
Syringe Pump Gears	Do not rotate properly	Syringe pump will not be able to work properly	8	Stripping, wearing	2	Replacing gears every certain period of time	1	16
Stepper Motors	Improper rotor motion	Syringe pump will not be able to work	10	Burn up, problems with bearings	1	Do not manipulate motors with improper tools	2	20
UV Bulbs	Does not produce enough light	Polymer mixture will not be cured on time, or evenly	8	Overheating, burned bulbs	1	Turn off the curing system when is not being used; replace bulbs when burned	1	8
Needle	Not extruding the material	Print job will not be able to proceed	6	Clogging	7	Frequent cleaning, or replacement of the needles	1	42
Printer Profile Modification	User introducing the coding	Printer will not print the desired shape; printer will not move properly	8	Wrong Coding	2	Do not change coding constantly	6	96

The results obtained with this analysis indicate that the highest risk priority number (RPN) corresponds to the printer profile modification. Even though the severity and the occurrence ranking of this step are relatively low, the detection ranking shows to be high. This detection parameter scored high because if the user is not well trained with programming knowledge, it would be difficult for someone to locate where the code is wrong. As a result, it is recommended not to modify this profile if it is not necessary.

The needle scored the next highest RPN, because the clogging might be very frequent if it is not well cleaned after every print job or if it is not replaced after use. Other components taken into consideration for the development of this analysis were the UV bulbs, the stepper motors, and the syringe pump gears. These components represent indispensable devices for the proper functioning of the 3D printer; therefore, their ranking on the severity parameter was relatively high. Nevertheless, the occurrence of these failures is not very likely, and the detection of their wearing or damage is very clear. As a result, the risk priority numbers of these components were not very high.

5. Design for Economics

For this project, the initial budget was $5,000.00. Nevertheless, the team only spent approximately sixty percent of the total budget. The expenses include the 3D printer purchase, which represents the most expensive element for the development of this project; the curing system components, the extruder head components, temperature sensor, camera, ABS filaments that were used to print several components necessary for the extruder head assembly, electrical components, and incidentals.

Table 2 on Appendix F, shows the break down costs of the different constituents of the final product assembly. It is important to mention that some of the components included in this table are not part of the final design; however, they are included on the final cost of this project. Since Team 19 was dealing with a research project, experimentation was an imperative portion for the progress of this project. As a result, some of the components listed in Table 2 were purchased for experimentation purposes; therefore if they did not work as expected, they were not used on the final design. Figure 2 shows the percentages of budget allocated for the devices and components purchased. As the figure indicates, the highest percentage on the chart indicates remaining money.

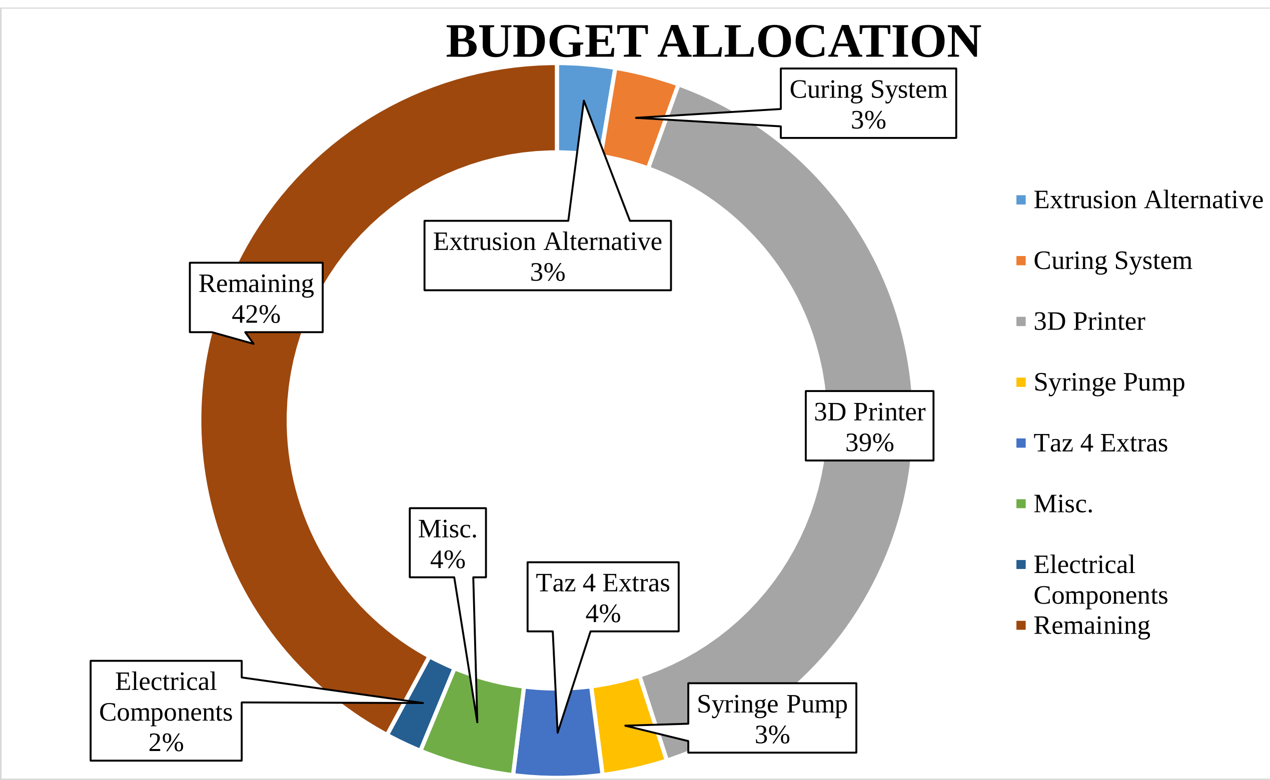


Figure 1: Budget Allocation

Some of the components that the team is currently not using on the final design are the Arduino Mega, the Inkshield, the cartridges, and some of the needles. Different sizes of needles were required to experiment with the width of the line specification parameter. The smaller the width of the line, the higher the resolution of the printed piece could achieve. Consequently, at the end of the testing phase, the team chose to use only the 22-gauge needle. Additionally, the Arduino board, the ink cartridges, and the Inkshield were also used for testing purposes. Since the experimentation with the Inkshield failed, these components are not part of the final design.

Project Total Cost = $2,891.60

3D Printer Actual Cost ≅ $2,518.81

The Project Total Cost depicted above indicates the cost of the project including testings' components, while the 3D Printer Actual Cost shows only the cost of the components that are currently being used on the final design.

Currently, there is not a device able to print the liquid precursor mixed with CNT's that Team 19 is printing. Even though, the Liquid Deposition Modeling (LDM) mechanism that Team 19 is using has been used before to print clay-like materials such as ordinary ceramics, and chocolate; those types of materials do not require a curing system integrated into the printer structure; as a result, comparing the price of the CNT Reinforced Ceramics 3D Printer with another product is not really applicable. Nevertheless, it can be said with certainty that the project that Team 19 is developing is very competitive, because none of the existing additive manufacturing techniques is able to print the novel material mixture that the team is working with.

6. Conclusion

The three sections developed on this report represent a significant part for the progress of the team's project. By performing these kinds of analyses, the team had the opportunity to see the current project design in a different perspective. While doing this, the team could have a closer look of the current assembly, and could forecast regarding the 3D printer performance. Additionally, an economic analysis was performed in order to find out how competitive this product can be compared to others.

In terms of manufacturability, the team concluded that by having a complex design, the results obtained will be more accurate. In addition, the printer that Team 19 is modifying, showed to have important benefits such as its compatibility feature; meaning that it allows the user to rapidly change the extruder head depending on which printing mechanism he wants to use, fused deposition modeling or liquid deposition modeling.

When it comes to reliability, there are some potential failures that can occur during the printer operation. Nevertheless, according to the results obtained on the FMEA analysis, even though the effects of some of these failures can cause a significant impact on the 3D printer performance, most of these failures are not very likely to occur, and they are not very difficult to handle.

The last analysis performed was the economics analysis. According to this analysis, Team 19 worked to maximize the value of all budget expenditures, and was able to acquire all necessary materials with 42% of the budgeted funds remaining. Additionally, since there are not similar 3D printing mechanisms, Team 19 concluded that comparisons with other 3D printers are not applicable, and therefore this project is considered competitive.

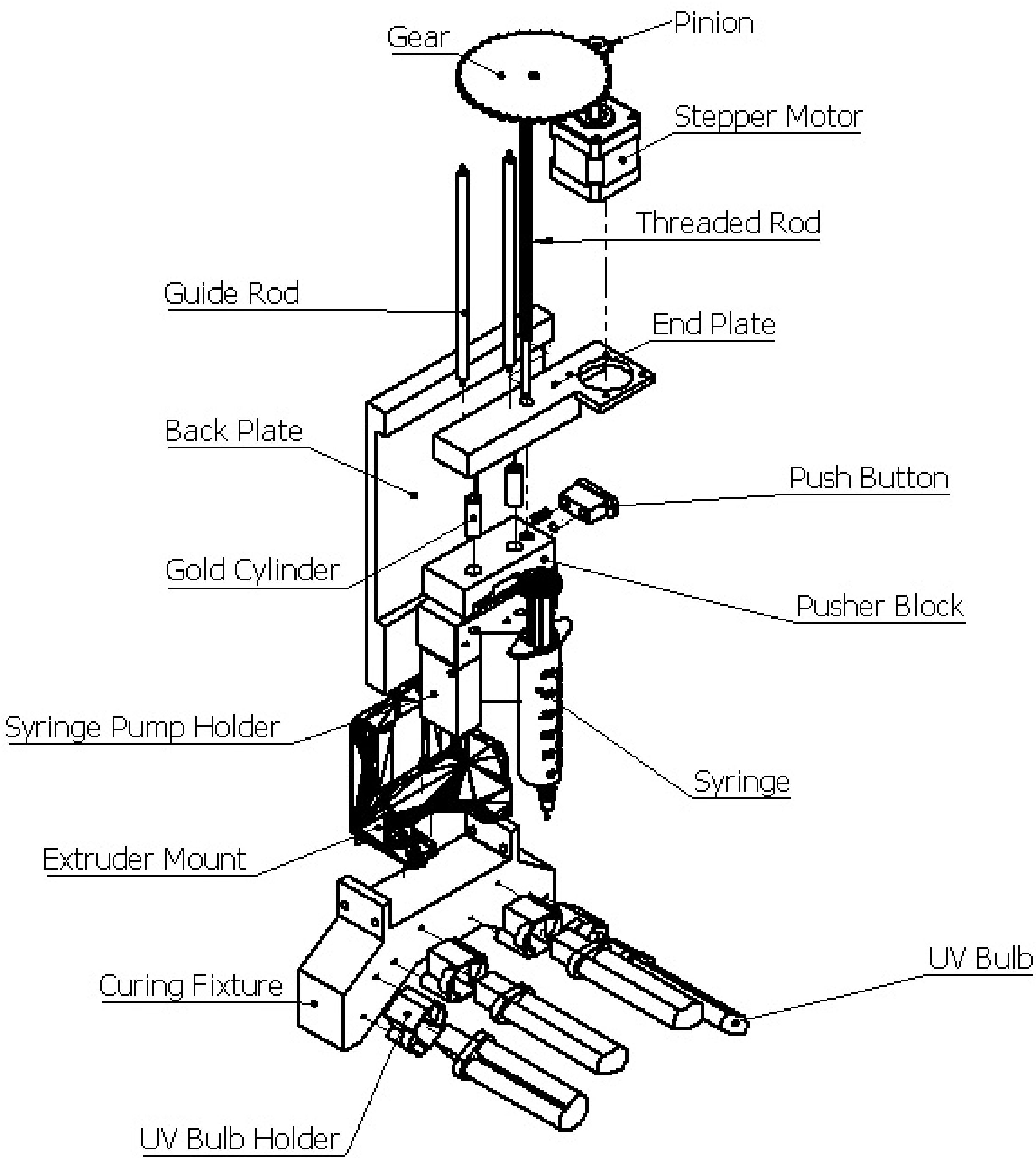
7. References

[1] R. Greenlee, "Design for Manufacturing - Guidelines," University of New Mexico, Albuquerque, 2002.

[2] B. Seymour, "MTTF, Failrate, Reliability and Life Testing," Texas Instruments Incorporated, Tucson, 2000.

[3] P. Colombo, G. Mera, R. Riedel and G. Soraru, "Plymer-Derived Ceramics: 40 Years of Research and Innovation in Advanced Ceramics," The American Ceramic Society, Trento, 2010.

Appendix A: Syringe Pump Exploded View with Integrated Curing System



Appendix B: Logitech HD Pro Webcam C920

a. Features

- Full HD video calling (up to 1920 x 1080 pixels)
- Full HD video recording (up to 1920 x 1080 pixels)
- Logitech Fluid Crystal ™ Technology
- Carl Zeiss® lens (20-step autofocus)
- Automatic noise reduction
- Low-light correction
- Tripod ready universal clip.

Appendix C: Arkon C-Clamp Camera Mount

a. Features:

- Compatible with all cameras with standard ¼” – 20 camera pattern
- Made of aluminum
- Can be installed in any table-like surface
- Firm grip that opens as wide as 2.5”, and closes as tight as 0.5”
- 12” gooseneck
- Allows a 360-degree rotation of the swivel ball adapter head

Appendix D: Etekcity 630 Digital Dual Laser Infrared Thermometer

a. Features:

- Dual laser targeting system
- Narrow distance-spot ratio offers accurate results at greater distances
- Safely measure hazardous or inaccessible objects
- Standard 9V battery offers 14 hours of cumulative use
- Auto-shutoff after 15 seconds to increase battery life
- Instant-read-displays results in less than one second.

Appendix E: Reliability Calculations

- $R\ (t) \rightarrow Reliability\ at\ time\ t$
- $\lambda \rightarrow Failure\ Rate$
- $MTBF\ \rightarrow Mean\ Time\ Before\ Failure$

Data: $R = 76.5\%,\ t = 5$ hours/print job

Calculation #1: Failure Rate

$$R(t) = e^{-\lambda t}$$

$$\ln(0.765) = -5\lambda$$

$$\lambda \Longrightarrow 0.0536\ failures/hour$$

$$\lambda\ \approx 5.36\ failures\ every\ 100\ hours$$

Calculation #2: Mean Time Before Failure

$$MTBF = \frac{1}{\lambda}$$

$$MTBF \approx \frac{1}{0.0536}$$

$$MTBF\ \approx 18.66\ hrs$$

$$18.66\ hrs\ \cong 4\ print\ jobs$$

.

Appendix F: Total Allocated Project Costs

Table 2 Total Allocated Project Costs

ITEM	TOTAL COST
ARDUINO MEGA	$45.95
INKSHIELD	$66.00
UV LIGHTS	$58.06
3D PRINTER	$1,995.00
NEEDLES	$83.30
THERMOMETER	$29.99
WEBCAM	$69.65
TRIPOD	$22.75
ABS FILAMENT	$171.80
UV LAMP	$89.00
UV SAFETY GLASSES	$74.24
SYRINGES	$9.50
BLUNT TIPS	$9.90
CARTRIDGES	$19.98
NEEDLE KIT	$19.93
NOZZLE	$19.00
BLUNT TIPS 22	$12.99
CRIMP-ON	$5.35
INSULATED DISCONNECTS	$2.99
HOOK UP WIRE	$8.56
STEEL SHEET	$12.63
USB ADAPTER	$37.60
DC POWER ADAPTER	$5.35
AC ADAPTER	$13.80
FEMALE ADAPTER	$4.99
CONN PLUG	$4.48
THREADED EXTENSION	$11.00
HEATER BLOCK	$15.00
TAXES/SHIPPING	$19.46
TOTAL	**2,891.60**