Massive 3D Depositor Senior Capstone Design

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# Abstract

In this report, we outline our plans to design and build a large (1’x1’x5’), high-temperature 3D printer capable of printing engineering-grade plastics, such as PEEK for $2,500. The 3D printing market is expanding rapidly due to the low cost of a 3D printer, fast production time, and low cost per print. Currently, most printers are only capable of printing weaker materials, due to the high temperatures and heated chamber required for the stronger plastics. The market is slowly expanding to stronger and higher temperature plastics, but with a very sharp increase in cost, or with a trade-off of a very small build volume, making these printers much less accessible to the common consumer. We look to remedy these problems by building a printer capable of printing PEEK with a build volume comparable to a $50,000 commercial printer at only $2,500. We hope to do this by combining a traditional, cheap printer movement system with high-temperature parts while employing novel solutions to counter the thermal issues and other issues spurred from the verticality of our print volume.

# Problem Definition

## Identification of Need or Opportunity

Over the past decade, 3D printing has become a popular manufacturing technique, due to its rapid per-unit production speed and low cost for both prints and the printer itself. However, traditional FDM printing is seldom used in projects requiring high structural strength or temperature due to the low printing temperatures (~200 °C), and thus weak plastics available for use in most printers. As the industry grows, more companies have been designing commercial-grade, high-temperature printers that cost in the five figures, making them unobtainable to most hobbyists and consumers. In this report, we outline the steps needed to build a 3D printer capable of printing large items (1’x1’x5’) at high temperatures (400 °C) while costing less than $2,500.

# Basic Research

## Existing Solutions

Below is a table of existing solutions of printers that can print PEEK [1]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| PEEK Printer Name | Build Volume (mm^3) | Max Extruder Temp (°C) | Max Bed Temp. (°C) | Max Chamber Temp. (°C) | Price |
| Intamsys Funmat HT | 1.76E+07 | 450 | 160 | 90 | 6,000 |
| Tractus3D T850P | 3.14E+07 | 450 | 175 | 80 | 15,000 |
| CreatBot PEEK-300 | 3.60E+07 | 500 | 200 | 120 | 17,000 |
| Apium P220 | 4.77E+06 | 540 | 160 | 220 | 46,000 |
| Zortrax Endureal | 3.60E+07 | 480 | 220 | 200 | 58,000 |
| Roboze One+400 Xtreme | 1.65E+07 | 500 | 150 | N/A | 50,000 |
| 3ntr Spectral 30 | 2.70E+07 | 500 | 300 | 250 | 110,000 |
| Essentium HSE 180 HT | 2.07E+08 | 550 | 100 | 200 | 149,000 |
| 3DGence Industry F340 | 2.65E+07 | 500 | 160 | 85 | 30,000 |
| MiniFactory Ultra | 1.07E+07 | 480 | 250 | 250 | 50,000 |
| Stratasys Fortus 450mc | 5.85E+07 | 450 | 250 | 350 | 160,000 |
| Aon-M2+ | 1.30E+08 | 450 | 200 | 135 | 50,000 |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Averages** | 5.01E+07 | 490 | 193 | 165 | 61,000 |
| **M3DD Printer** | 1.12E+08 | 450 | 200 | 80 | 2,500 |

All the commercial PEEK printers we could find have some tradeoff that made it unappealing. The most affordable printer, the Intamsys Funmat HT, has a build volume 10x smaller than ours at double the price. The printer that was closest in build volume to ours costs $50,000, making it far from affordable. We believe we are striking a middle-ground no other company has touched as of yet.

## Market Analysis

In 2018, the 3D printing industry was worth 1.53 billion. By 2026, it is predicted to more than double to 3.78 billion. [2] While printer software and related services make up part of that, the printers themselves account for half the market. 3D printing is expanding into even the largest of industries, such as medical, automotive, and oil (which is our focus). [3] As shown by the large number of companies that are trying to expand into printing high-temperature plastics, printing PEEK and similar plastics has a promising future since it overcomes a lot of the strength and temperature shortcomings of lower-temperature plastics.

# Design Requirements

## Functionality Requirements

* The system should respond to movement commands in the X, Y, Z, and Extruder directions
* The system should be able to heat nozzle up to 450 °C, bed up to 200 °C, and chamber up to 80 °C
* The system should be able to print all common filament types (PLA, ABS, PETG) with and without the heated chamber
* The system should be able to print PEEK and PSU objects
* The system should have a total usable print volume of 300x280x1330mm
* The system should be able to operate at the maximum chamber temperature for at least 3 days continuously without overheating or having part failure

## Usability Requirements

* The system should be able to operate on a local 20A breaker without the heated chamber and with the heated chamber on three separate 20A circuits
* The system will have thermal protection for the hotend, heated bed, and chamber
* The system will have fused connections in the event of a short circuit

## User Experience Requirements

* Users can monitor and control the temperature and movement of the system locally through the LCD
* Through a web interface, the user can:
* Control nozzle, bed, and chamber temperature
* Control X, Y, Z, and E movement
* Send commands
* Start, Stop, and monitor prints
* View print through real-time system

# Initial Concept Generation

## Frame

For a frame, aluminum extrusions are the de-facto standard for 3D printing frames due to their structural rigidity, low cost, and high functionality. We chose aluminum frames for the movement system and any structural pieces needed in a traditional FDM 3D printer. For the chamber frame, we chose to use a server rack. We found a server rack out-competed aluminum extrusions considering the overall size and mounting ease versus cost. This is a piece that would be trivial to replace given the required critical dimensions if another unit needed to be manufactured. The server rack will have insulation mounted to the outside of it and will provide a structural foundation for mounting our aluminum extrusion-based movement system.

## Movement System

To move the hotend around the build volume, we are using a cartesian movement system with a pulley/belt combination. A coreXY printer would require an assembly the size of the bed volume to move through the entire print volume. This drastically increases complexity and would leave no room for auxiliary components like the heating elements. A delta printer would work in theory, but we will lose a lot of our build volume because of the circular build platform. For the cartesian design, the X and Y axes are easy to design and build as they fall within the typical sizes. However, the Z-axis requires a lot of engineering due to its unorthodox size. Most cartesian printers use a lead screw since it is sturdy, cost-effective, and self-locking in the event of power loss. If we were to use this method, we would need a 5’ lead screw, which would bend in the middle, no matter how perfectly the screw is made. To eliminate the lead screw, we want to use the most common Z-movement system for delta printers: a pulley/belt combination. However, this has its issues. It’s not as cheap, will require more motor torque to move if our X-carriage gets too heavy, and the X-carriage will fall in the event of power loss. To solve these issues, we plan to add a counterweight to reduce the amount of power needed to move the X-carriage and to stop the X-carriage from dropping in a power-loss event. We also plan to add spring-loaded fail-closed switches to the top and bottom to catch the X-carriage to prevent it from bottoming or topping out.

## Computing

For the intelligence of our printer, we chose an SKR 2 Turbo due to its high ability to be customized along with TMC2099 stepper motors. They can drive 2A, which is the maximum drive current for our SKR 2. The SKR 2 allows us to connect to OctoPrint to monitor prints through a web interface and connect an LCD for local control and monitoring, per our design requirements. We plan on running Marlin firmware since it is open-source, highly customizable, and supports thermal protection. We are also going to host OctoPrint on a RaspberryPi running OctoPi, with custom software to run our chamber thermal protection, since Marlin’s chamber thermal protection may not cover our complex-use scenarios, such as someone opening the chamber during a print. This will cause a drop in the chamber temperature, which Marlin would register as an error and stop the print, but the act of opening the chamber itself isn’t a cause for triggering the thermal protection.

## Heating System

The nozzle and bed heating elements by themselves will raise the internal temperature of the printer above ambient, but an additional heating element is needed to raise the chamber temperature to the level required to print PEEK. We are currently looking at using household space heater elements, as they only get up to between 120°C-200°C for safety reasons, which would be our ideal temperature. However, we have concerns about the safety of their construction and need to make sure they can get the entire chamber temperature to 80°C. Our preliminary anecdotal tests show that they should meet the temperature requirements, but we aren’t settled on a heating element until we finish our complete thermal analysis. To contain the heat, we are looking at two different options for insulation. The first option is foil-faced polyisocyanurate rigid foam insulation, as it has a similar thermal conductivity coefficient similar to air, as shown in section 5.3. However, this insulation not only is very bulky, but flakes off with time, which will reduce print adhesion, and thus print quality. The second option is a fiberglass and wood insulation combination, as it would solve our flaking issue and be much slimmer. However, while we know that the fiberglass/wood insulation won’t insulate as well as the foam, we haven’t determined if choosing a more heavy-duty heating element would allow this alternative insulation method to work. See a more complete thermal analysis in section 5.3

## Thermal Management

While we want our chamber to be hot, certain components should not get hot, such as the stepper motors. To cool our stepper motors, we are mounting the possible ones, such as our Z and Y motors, outside of the build chamber and only have the shaft inside the chamber. This would allow us to keep those stepper motors at ambient temperature. The X and the E motors can’t be located outside the heated chamber, so we are using Peltier Plates to cool those motors. The cold side would be on the motor, and the hot side would be attached to a heatsink and fan to reduce the temperature, whose heat would add to the chamber temperature. Additionally, the temperature of the camera that monitors the print should be thermally managed. It doesn’t get anywhere near as hot as the motors, but to reduce the temperature, we surrounded the camera in aluminum tape to minimize the freshly heated air warming up the camera.

# Preliminary Analysis

## Initial Power Analysis

We plan on splitting up the power into three circuits to satisfy the design requirements. We are having two A/C circuits for our chamber heating elements, and then a 3rd A/C circuit for all other components. The heating elements of the space heaters we are planning on using are 1500W each. At 120V, this yields per space heater, keeping us below our 20A breaker design requirement. We are assuming to use 2 space heaters, although we won’t be able to know for sure until we complete full the thermal analysis.

For the DC components, we need to pick an adequate power supply. Below is a table of the power draw requirement estimates for each component. For the voltage conversions, we are assuming a worst-case efficiency of 70% for our buck converters. [4] These currents are also over-estimates assuming max-load on each component. We won’t be able to test each unit for the actual power draw (such as the raspberry pi and SKR board until we can power them up). We are only able to off manufacturer specifications and tests done by 3rd parties.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Part | Voltage/unit | Amperage/unit (with conversion efficiency included) | Quantity | Total Amperage Used |
| Name 17 2A motor | 24 | 2 | 3 | 4 |
| Nema 17 motor (high power) | 24 | 0.58 | 2 | 1.74 |
| SKR Board | 24 | 0.5 | 1 | 0.5 |
| Heater Cartidge | 24 | 2.08 [5] | 1 | 2.08 |
| Space heater fans | 12 | 0.33 | 2 | 0.858 |
| RPi | 5 | 0.4 [6] | 1 | 0.52 |
| LED Strip | 5 | 0.06 [7] | 5 | 0.39 |
| Peltier Plates (@ 5V) | 5 | 1.5 [8] | 2 | 3.9 |
| Bed heater element (AC power) | AC | 4.1 | 1 | 4.1 |
|  |  |  | **Summation:** | 18.088 A |

We are using 18.088A for the primary AC connection. We need 13.99A for our power supply since the heated bed doesn’t contribute to the load on the power supply. The power supply we chose was a Meanwell 24V/21A power supply. This gives us breathing room, so we aren’t always stressing our power supply and the price difference between a 24V/15A and 24V/21A power supply was negligible.

## Initial Movement Analysis

## Initial Thermal Analysis

For our initial thermal analysis, we had two ideas for our insulation types, as mentioned in section 4.4, the foil-faced polyisocyanurate rigid foam insulation and the fiberglass/wood combination. We want to determine which method better retains heat, even though we would prefer the fiberglass/wood insulation due to the flaking and bulkiness of the foil-faced foam insulation. To do this, we calculated the heat transfer rate for each type of insulation for a single side of the chamber. This will let us know which insulation type is more effective.

We assumed the outside ambient temperature was 72°F, or 22.2°C, and the inside temperature was 80°C, our maximum chamber temperature as listed in the design requirements.

|  |  |  |  |
| --- | --- | --- | --- |
| Variable | Value | Units | Name |
| T­i | 80 | C | Temperature inside |
| T­o | 22.2 | C | Temperature outside |
| Cheight | 1.651 | m | Chamber height |
| Cwidth | 0.535 | m | Chamber width |
| Clength | 0.648 | m | Chamber length |
| A | 1.069 | m­­2 | Cross-sectional area |
| Lfoam | 0.1524 | m | Foam depth |
| Lfiberglass | 0.0254 | m | Fiberglass depth |
| Lwood | 0.00635 | m | Wood depth |
| ho | 12 [9] | W/m2⋅K | Heat transfer coefficient outside |
| hi | 120 [10] | W/m2⋅K | Heat transfer coefficient inside |
| Kfoam | 0.026 [11] | W/m⋅K | Foam thermal conductivity |
| Kfiberglass | 0.0316 [12] | W/m⋅K | Fiberglass thermal conductivity |
| Kwood | 0.12 [13] | W/m⋅K | Wood thermal conductivity |

The heat transfer rate of the foil-faced foam is:

The heat transfer rate of the fiberglass/wood is:

The heat transfer rate for the foil-faced foam was lower than the one for the fiberglass/wood, making it a better insulator. This is not surprising, as its thermal conductivity coefficient is very similar to that of air, which is about 0.025 at our needed temperature. [14] To determine if we need to use the foil-faced foam, we need a more complete thermal analysis before we can rule out using the fiberglass/wood combination, since this insulation combination may still work with our current heating element choice. Additionally, we could also choose a larger heating element if necessary. Although the foil-faced foam is a better insulator, it still has the flaking and bulk problems listed in section 4.4, incentivizing us to continue more in-depth thermal analysis until we are certain we have to use the foam.

# Schedule

|  |  |  |
| --- | --- | --- |
| Week | Date | Timeline |
| Week 1 | 01/18 – 01/21 | Capstone introduction |
| Week 2 | 01/24 – 01/28 | Project selection |
| Week 3 | 01/31 – 02/04 | Part selection for movement system  CAD all parts for movement system for future analysis  Setup project requirements  Initial budget |
| Week 4 | 02/07 – 02/11 | Continue CADIng all parts for the movement system  Design case for mounting electronics  Determine a Z-axis mechanism for movement |
| Week 5 | 02/14 – 02/18 | Design Y tensioning mechanism  Install movement system into frame  Preliminary report/presentation |
| Week 6 | 02/21 – 02/25 | Make movement system work  Install electronics/ run wiring |
| Week 7 | 02/28 – 03/04 | Debug movement system  Design/replace parts that need it |
| Week 8 | 03/07 – 03/11 | Calibrate printer w/o heated chamber  Start thermal analysis |
| Week 9 | 03/14 – 03/18 | Determine thermal materials and order it  Critical design report/presentation |
| Week 10 | 03/21 – 03/25 | Install thermal materials and get the printer up to temperature |
| Week 11 | 03/28 – 04/01 | Run test prints at max temperatures |
| Week 12 | 04/04 – 04/08 | Debug thermal/electrical issues |
| Week 13 | 04/11 – 04/15 | Debug thermal/electrical issues  Create final report |
| Week 14 | 04/18 – 04/22 | Work on final report and presentation |
| Week 15 | 04/25 – 04/29 | Finish final report/presentation and dry run presentation |

# Preliminary Budget

|  |  |  |
| --- | --- | --- |
| Name | Cost | Quantity |
| SKR 2 | 49.99 | 1 |
| Rpi | 34.99 | 1 |
| Buck Converter | 9.99 | 1 |
| LCD | 16.95 | 1 |
| SSR | 10.49 | 3 |
| Fuses | 8.47 | 1 |
| Power Supply | 35.99 | 1 |
| Aluminum Extrusions | 23.25 | 2 |
| High power motor | 13.99 | 2 |
| Low power motor | 10.99 | 2 |
| Extruder | 12.99 | 1 |
| Peltier Plates + heatsinks | 31.35 |  |
| 24V fans | 11.99 | 1 |
| pi camera + 6ft cable | 15.04 |  |
| End stops | 9.99 | 2 |
| Mosquito hotend | 149.99 | 1 |
| mosquito thermistor | 69.99 | 1 |
| heater cartridge | 15.99 | 1 |
| led strip | 11.92 | 1 |
| Garolite | 15.95 | 2 |
| Heated bed | 159.99 | 1 |
| wires | 20 | 2 |
| Leadscrews | 55 | 2 |
| anti-backlash nuts | 10.98 | 1 |
| Insulation | 100 | 1 |
| Kaolin cloth | 20 | 1 |
| High temp belt | 11.99 | 1 |
| high temp wheels | 21.99 | 1 |
| breaker | 9.99 | 1 |
| outlets | 9.99 | 1 |
| switches | 9.99 | 1 |
| sheet metal | 30 | 1 |
| frame | 0 | 1 |
| bowden setup | 19.99 | 1 |
| printed parts (estimate) | 100 | 1 |
| wifi adapter | 10.55 | 1 |
| BLTouch | 40.26 | 1 |
| capacitors | 11.65 | 1 |
| **Total:** | **1626.43** |  |
| **30% price increase** | **2114.359** |  |

# Conclusions and Next Steps

The next steps are the continue following our schedule. In the coming weeks, we will build our movement system and verify functionality as a 3D printer without a heated chamber. We hope to have this done before the critical design report is due. After that, we will be able to finish our full thermal analysis (if we haven’t already done so by then) after we have determined our movement systems and begin designing our heated chamber. Of course, when building our movement system, we are selecting components that can withstand temperatures of 80 °C. At the time of writing, we are perfecting the design of our Z-movement system, overcoming the obstacles of a very tall build volume.

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