3D PEEK PRINTER

Preliminary Design Report

CMPE 499 – Engineering Design and Devlopment

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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.

1. Problem Definition

1.1 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.

2. Basic Research

2.1 Existing Solutions

Below is a table of existing commercially available 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

Table 1: Commercial PEEK Printers

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.

2.2 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.

3. Design Requirements

3.1 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

3.2 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

3.3 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

4. Initial Concept Generation

4.1 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.

4.2 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.

4.3 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.

4.4 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 to air [4] [5]. 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 will have a high rate of heat transfer than 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.

4.5 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.

5. Preliminary Analysis

5.1 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 $\frac{1500W}{120V} = 12.5A$ 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. [6] 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 [7]	1	2.08
Space heater fans	12	0.33	2	0.858
RPi	5	0.4 [8]	1	0.52
LED Strip	5	0.06 [9]	5	0.39
Peltier Plates (@ 5V)	5	1.5 [10]	2	3.9
Bed heater element (AC power)	AC	4.1	1	4.1
			Summation:	18.088 A

Table 2: Power Analysis

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.

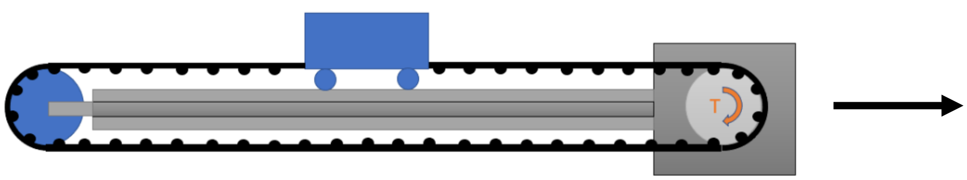
5.2 Initial Movement Analysis

As mentioned in our initial concept generation, We plan to use 3 separate belt/pulley systems to control our 3 axes of motion. Each system would require a stepper motor to move the bed or carriages. By creating a free body diagram of the carriage, we will be able to find the needed torque of the motor in the x-direction.

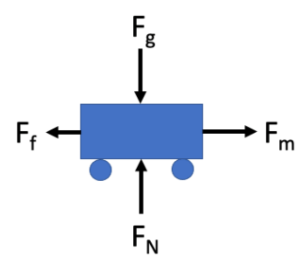
Variable	Value	Units	Name
m_c	0.297	kg	Mass of the carriage
r_m	0.0047	m	Radius of the Motor
a_{max}	0.5	m/s^2	Maximum acceleration
μ	0.0015 [11]	N/A	Coefficient of friction
g	9.81	m/s^2	Gravitational acceleration

Table 3: Movement Values

x-direction movement system



Free Body Diagram



Where $F_g = Weight\ of\ the\ Carriage = m_c * g = 0.297 * 9.81 = 2.62$ N

$$\sum F_y = 0 = F_N - F_g \longrightarrow F_N = Normal\ Force = F_g = 2.62\ N$$

$$F_f = Force\ of\ Friction = \mu * F_N = 0.0015 * 2.62 = 3.93 * 10^{-3}\ \text{N}$$

$$\sum F_x = m_c * a_{max} = 0.297 * 0.5 = 0.149 = F_m - F_f \longrightarrow F_m = 0.1485 + 3.93 * 10^{-3} = 0.152\ N$$

$$T_m = r_m * F_m = 0.0047 * 0.152 = \mathbf{0.714\ Ncm} \longrightarrow \text{Required Torque by our Stepper Motor}$$

While the calculation for required torque is straightforward, a much more in-depth analysis of our stepper motors needs to take place to calculate the amount of torque our stepper motors can provide at the desired speed and acceleration of our carriage. Variables such as max rotational speed, number of microsteps per full step, belt tooth and pitch sizes, and motor efficiency all need to be taken into account. Similar calculations will also need to take place in determining the required torque by our stepper motor in the y and z-direction as well.

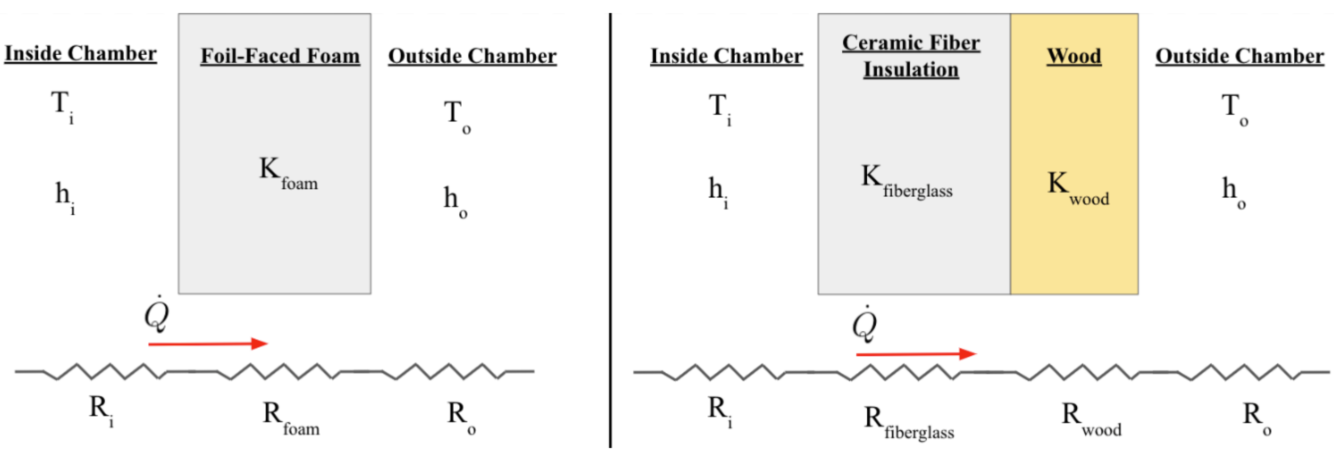
5.3 Initial Thermal Analysis

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. We also estimated our convection heat transfer coefficients, since it is dependent on the airflow, and we have not determined how the air will flow in our system yet. This analysis is simply to show the difference in the effectiveness of our two methods of insulation.

Variable	Value	Units	Name
T_i	80	C	Temperature inside
T_o	22.2	C	Temperature outside
C_{height}	1.651	m	Chamber height
C_{width}	0.535	m	Chamber width
C_{length}	0.648	m	Chamber length
A	1.069	m^2	Cross-sectional area
L_{foam}	0.0762	m	Foam depth
$L_{fiberglass}$	0.0254	m	Fiberglass depth
L_{wood}	0.00635	m	Wood depth
h_o	12 [12]	$W/m^2 \cdot K$	Heat transfer coefficient outside
h_i	120 [12]	$W/m^2 \cdot K$	Heat transfer coefficient inside
K_{foam}	0.026 [5]	$W/m \cdot K$	Foam thermal conductivity
$K_{fiberglass}$	0.0316 [13]	$W/m \cdot K$	Fiberglass thermal conductivity
K_{wood}	0.12 [14]	$W/m \cdot K$	Wood thermal conductivity

Table 4: Thermal Values



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

$R_{total\_foam} = \mathrm{R_i} + \mathrm{R_{foam}} + \mathrm{R_o}$ where $R_i = \frac{1}{\mathrm{h_i} * \mathrm{A}}$, $R_{foam} = \frac{\mathrm{L_{foam}}}{\mathrm{K_{foam}} * \mathrm{A}}$, and $R_o = \frac{1}{\mathrm{h_o} * \mathrm{A}}$

$$\dot{\mathrm{Q}}_{\mathrm{foam}} = \frac{\mathrm{T_i} - \mathrm{T_o}}{R_{total}} = \mathbf{20.45}\ \boldsymbol{W}$$

The heat transfer rate of the fiberglass/wood is:

$R_{total\_fiberglass} = \mathrm{R_i} + \mathrm{R_{foam}} + \mathrm{R_o}$

where $R_i = \frac{1}{\mathrm{h_i * A}}$, $R_{fiberglass} = \frac{\mathrm{L_{fiberglass}}}{\mathrm{K_{fiberglass} * A}}$, $R_{wood} = \frac{\mathrm{L_{wood}}}{\mathrm{K_{wood} * A}}$, and $R_o = \frac{1}{\mathrm{h_o * A}}$

$$\dot{\mathrm{Q}}_{\mathrm{fiberglass}} = \frac{\mathrm{T_i} - \mathrm{T_o}}{R_{total}} = \mathbf{65.17\ W}$$

By using the thermal resistivity method of analysis, we were able to compare the effectiveness of each method of insulation. 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 the foil-faced foam has a much larger thickness, resulting in a lower heat transfer rate. 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.

6. 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

Table 4: Schedule

7. Preliminary Budget

Name	Cost	Quantity	Name	Cost	Quantity
SKR 2	49.99	1	Garolite	15.95	2
Rpi	34.99	1	Heated bed	159.99	1
Buck Converter	9.99	1	wires	20	2
LCD	16.95	1	Leadscrews	55	2
SSR	10.49	3	anti-backlash nuts	10.98	1
Fuses	8.47	1	Insulation	100	1
Power Supply	35.99	1	Kaolin cloth	20	1
Aluminum Extrusions	23.25	2	High temp belt	11.99	1
High power motor	13.99	2	high temp wheels	21.99	1
Low power motor	10.99	2	breaker	9.99	1
Extruder	12.99	1	outlets	9.99	1
Peltier Plates + heatsinks	31.35		switches	9.99	1
24V fans	11.99	1	sheet metal	30	1
pi camera + 6ft cable	15.04		frame	75	1
End stops	9.99	2	bowden setup	19.99	1
Mosquito hotend	149.99	1	printed parts (estimate)	100	1
mosquito thermistor	69.99	1	wifi adapter	10.55	1
heater cartridge	15.99	1	BLTouch	40.26	1
led strip	11.92	1	capacitors	11.65	1

Table 5: Preliminary Budget

Total cost: 1,701.43

With a 30% price increase, the total cost is $2,211.86

8. Conclusions and Next Steps

The next steps are to 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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