UNIVERSITY OF CALIFORNIA, SAN DIEGO

Design of a Screw Extruder for Additive Manufacturing

A Thesis submitted in partial satisfaction of the requirements for the degree

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in

Engineering Sciences (Mechanical Engineering)

by

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The Thesis of Dylan T.J. Drotman is approved and is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2015

EPIGRAPH

Do not go where the path may lead,
go instead where there is no path
and leave a trail.

Ralph Waldo Emerson

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ABSTRACT OF THE THESIS

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Dylan T.J. Drotman

Master of Science in Engineering Science (Mechanical Engineering)

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Professor Miroslav Krstic, Chair

Our aim is to show that the screw extrusion process is comparable to current FDM 3D printing processes by implementing an innovative design along with an advanced control algorithm. A thermistor array was used to detect the temperature profile along the barrel during the extrusion process for feedback. This provided

information in regards to the location of the melting point during extrusion. The current prototype was able to achieve open loop extrusion out of a 0.2mm diameter nozzle with a maximum output flow rate of 7.14 mm/second and retain a controlled temperature profile using bang-bang control throughout the extrusion process.

1. INTRODUCTION

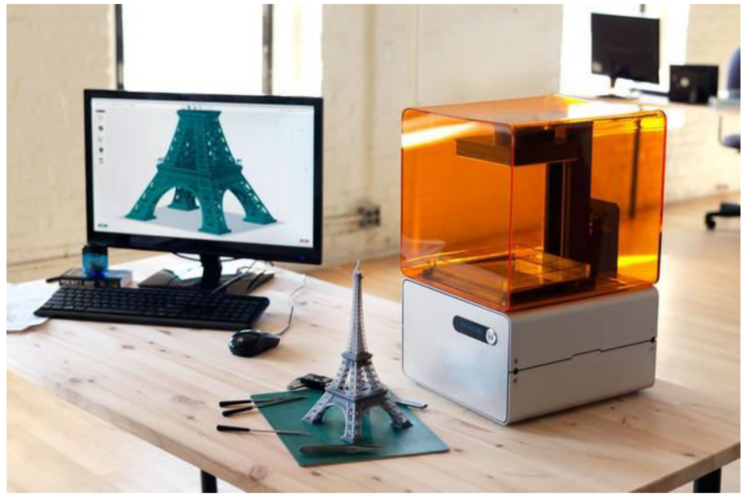

Figure 1: Formlabs 3D Printer Printing the Eiffel Tower [7]

3D printing is the process of taking a designed digital model and creating a three-dimensional physical object usually by adding material. Material is successively built up layer by layer to form a 3D object. Traditional manufacturing approaches are subtractive; material is removed to form a 3D shape. The additive approach allows for complex shapes to be actualized and reduces the amount of wasted material.

To 3D print an object, the first step is to use 3D modeling software such as Autodesk Inventor, Solidworks, or Google SketchUp to develop a 3D representation of the object. Next, the model is converted into an STL file format which describes the outer surface of the object. The model can then be opened on host software such as Repetier which allows the user to rotate the object into the most structurally sound orientation for the print. Next, a slicing software such as Slic3r slices the object into layers for the printer extruder to follow. The user can also adjusts printing parameters such as print speed, layer height, and material density using this software.

The host software converts this information into G-code that the 3D printer can follow and the part is ready to print. Each layer will progressively be built up until the full 3D printed part is created.

There are many different 3D printing processes currently available, each with their associated pros and cons. The choice for the most appropriate 3D printing process to use is determined by the application that the part will be used for.

Photopolymer processes use a UV curable photopolymer that solidifies when exposed to a specific wavelength of light. These processes create high resolution parts but are limited in materials that can be used. Two of these processes are stereolithography which uses a selective UV light to solidify a photopolymer from a vat of liquid and solid ground curing which uses a photomask for each layer and solidifies the layer using UV light [2].

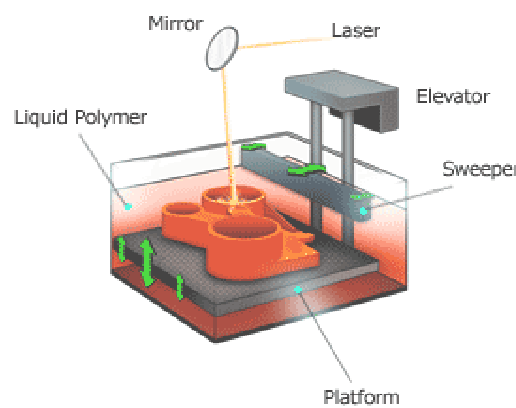

Figure 2: Photopolymer 3D Printing Process [5]

There is also deposition based fabrication which deposits material in an additive manner to build up a 3D object. This fabrication process uses a wider variety of materials but lacks the ability to create precise, overhanging objects. Fused deposition modeling is the process of feeding a spool of filament into a heated chamber which is then extruded out of a nozzle layer by layer. Syringe based extrusion uses pressure to force a liquefied polymer through a nozzle [2].

Powder based fabrication uses a powder and a binding agent to build each layer of the 3D part. Selective laser sintering is the process of using a CO_2 laser to solidify powder layer by layer. There are two pistons in the system; one is used to push the material up to form each individual layer and the other piston moves down to allow the object to form. A laser beam is used to solidify material as the elevator moves down. The benefit of using this process is there is no need to use support material. The object is always surrounded by powder allowing for construction of intricate shapes. Selective inkjet binding lays uses a liquid binder to bond thin layers of powder [2].

Laminated object manufacturing is the process of cutting out solid layers and bonding each of these layers together using an organic compound [2]. A laser or knife is used to cut out each layer and then glue each layer down one by one. The sheet is adhered to the previous layers using a heated roller. By repeating this process, a 3D model can be created out of paper, plastic or metal. The benefit of using this process is it is low cost because these materials are easily accessible. This manufacturing process can cut out precise layers, however, it is very wasteful of material.

1.1 Screw Extrusion Benefits

Our goal is to design a small scale screw extruder that will improve extrusion speed, part quality and process repeatability for a low cost 3D printer. The small design and advanced controls will contribute to faster and higher quality 3D prints for a wider variety of materials. Potentially, an accurate control of the temperature, pressure and transport of plastic pellets throughout the process help to maintain material uniformity at the outlet. Furthermore, better resolution and higher printing speed are possible compared to existing plastic printers. We hope to improve parameters that are bottlenecking current 3D printing processes.

There are other processes available now which result in high resolution part such as stereolithography, however, their limitation is the materials that are currently available. New photopolymer-based materials are becoming available for these processes, but the technology has not developed enough yet. Using pellet based extrusion processes allows for a wider variety of materials to be used.

Manufacturers use plastic pellets to create specific diameter spools of filament for deposition based processes. Because the filament has to go through this extra manufacturing process, filament is more expensive than pellets. If we skip this step for creating spools of filament, the material becomes roughly 50-80 percent cheaper depending on the distributor and quantity of material. Material is purchased on a regular basis for 3D printing so the low material cost has a large impact over the long term.

Figure 3: Extrusion Bot Filament Screw Extruder

There are screw extrusion based processes available for 3D printing, but as a separate step from the 3D printer. Filabot and Extrusion Bot are two example systems. These systems convert pellets into spools of filament which is then wound up into spools and used on FDM based 3D printers. These are very large screw extrusion machines which costs $800. By using a small scale screw extruder mounted on the 3D printer, we will be able to skip the step of converting pellets to filament. The small screw extruder will cost the same as a standard FDM extruder.

Syringe based extrusion requires an interruption during the process in order to refill the extruder chamber. With screw extrusion, a small amount of material is processed at a time therefore allows for a homogeneous feeding process which also allows for more precise control over the material rheology.

Screw extrusion enables a higher pressure build up than fused deposition modeling which increases the rate of extrusion. The capabilities of the screw extruder to build up high pressure also allows for smaller nozzles to be used, therefore increasing the resolution of the prints.

Existing literature does not commonly address the control of the stop and start of extrusion-based 3D printing on-demand. A hybrid extrusion force-velocity modeling and tracking control for the fabrication of graded material parts is developed in [9] using a first order differential equation to represent the plunger dynamic for a SBE. Some of this approach is proposed by [10] with a robust tracking of the extrusion force to recover constant flow disturbances whereas [11] considers an unknown transfer function gain with an adaptive control strategy. Several issues regarding FDM are discussed in [12], [13] and references therein, including the clogging due to formation at the nozzle, appearance of bubbles, density inhomogeneity, tracking of short timescale process variations, and prediction of anomalies such as material overflow and underflow for diverse applications. Thermal control is left out of most prior studies which are commonly based on empirical models.

For this process, the goal for the controls is to regulate the nozzle output temperature and pressure in order to achieve fast extrusion of a filament with the desired properties such as its viscosity, thickness and uniformity. We emphasize that due to the strong interaction between the mass, momentum and energy balance in this process that the design of high performance feedback control methodology still remains challenging and hard to achieve. Most of the existing control mechanisms are based on oversimplified black-box models that only operate around a given set point. These approaches also do not take into account each individual print. We can use the knowledge about the print to our advantage by adjusting the motor speed and temperature accordingly. Few of these control approaches tackle the dynamical modeling and control for large scale machines. Using advanced control techniques will provide better performance and allow to move beyond the FDM and the Syringe based extrusion processes.

1.2 Screw Extrusion Process

Material is stored in an external large hopper and fed into the extruder through the inlet. The pellets flow directly into the screw channel and are transported by the screw towards the nozzle opening. The heater near the nozzle heats up the barrel and screw which liquefies the polymer as the pellets are transported. Once the material has liquefied and exits the screw channel, the material enters the buffer chamber. The

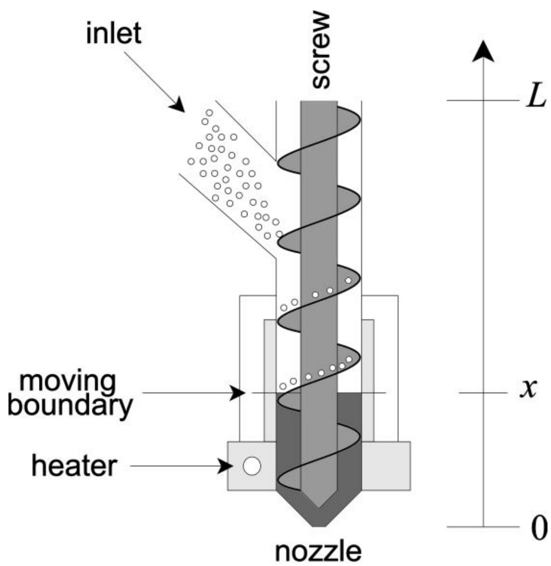

Figure 4: Depiction of the Screw Extrusion Process

buffer chamber represents the empty spacing between the bottom of the auger and the nozzle. The rotation of the motor compresses the polymer in the buffer chamber, forcing the material through the small opening in the nozzle.

The flow in an extruder can be separated into geometrical regions called the partially filled zone and fully filled zone. We can model the thermal phenomena for the partially filled zone and fully filled zone separately but similarly. The partially filled zone is the conveying region for the solid pellets and exposed to air pressure. In this zone, the rotation of the auger is only used for transport of the pellets. The fully filled zone represents the melting zone. In this zone, the rotation of the auger is used for conveying material. A pressure gradient in the material is formed from nozzle resistance, causing extrusion. Although in reality, there is a transition phase between the solid and liquid, simplifying the material phase transition as a boundary will help develop a model for the system.

1.3 System Considerations

Isolating the forces on the auger and the material will provide a better understanding for the extrusion process. By forcing pellets against the side of the barrel, there will be a large pressure build up and maximum output flow because the flow will be driven by drag. Maintaining a consistent inlet flow into the screw channel affects the output flow. Cavitation will occur at the outlet when the inlet flow is inconsistent. Some of the other forces affecting the output flow are gravity, plastic-barrel-screw interface shearing, expansion caused by air pockets, centrifugal force (negligible at slow speeds), and back pressure caused by reduction in diameter at the nozzle tip.

Heat sources and sinks are the main contributors towards the consistency of the material at the output. Convection and conduction from the barrel and screw play the largest role for heat in the screw extruder. The amount of time the material is exposed to these heat sources affects the material properties at the outlet and the consistency of flow at the inlet. If the temperature is two high, the material may melt at the inlet and jam the auger. The high temperature can also cause the material to burn and become less viscous. Having the temperature too low will prevent extrusion by causing a jam. The material itself is a heat sink as it absorbs the heat during the extrusion process. Other heat sources include the temperature and humidity of the environment, the screw-barrel shearing and adjacent polymer conduction.

In order to compact the viscous fluid and maintain consistent flow, a buffer chamber must be introduced near the outlet. This space allows for the viscous fluid to compress, removing air pockets which allows for consistent flow at the output. The down side to having a buffer chamber is the post-extrusion pressure will cause the material to ooze. Pressure exists after the auger stops causing material to leak. Fast reversal of the auger is needed during a 3D print to prevent oozing. If there was no buffer chamber in the system, then the motor must produce high enough pressure along the auger to compact the material before it reaches the nozzle tip. Oozing is also affected by the viscosity of the material. If the temperature is low enough, the material will be viscous enough to prevent oozing out of the small opening in the nozzle when the extruder is stopped.

1.4 Material: Polylactic Acid

There are many different plastic pellets available that can be used for extrusion but the most standard materials used for 3D printing with FDM are ABS and PLA plastic. PLA is a good candidates for screw extrusion because of its low melting temperature. The viscosity of PLA also decreases with an increase in temperature therefore giving a low melt viscosity [4]. Some material properties for PLA can be shown below [5]:

Table 1: PLA Properties [5]

PLA Properties	Value	Units
Glass Temperature	59	C
Melting Temperature	163	C
Tensile Strength	630	Kgfcm-2
Ultimate elongation	6	percent
Izod impact strength	2	Kgf cm cm-2
Rockwell Hardness	119	
Vicat Softening point under 1kg load	63 (150)	C (annealed)
Melt flow rate E method: 190C	10	g/10min

The main concern for this extrusion process is to have a consistent flow at the output at the right temperature. PLA mixed with LDPE at different ratios affect the material during the screw extrusion process [4]. However, for our research, we will only be concerned with PLA100 which is 100% PLA.

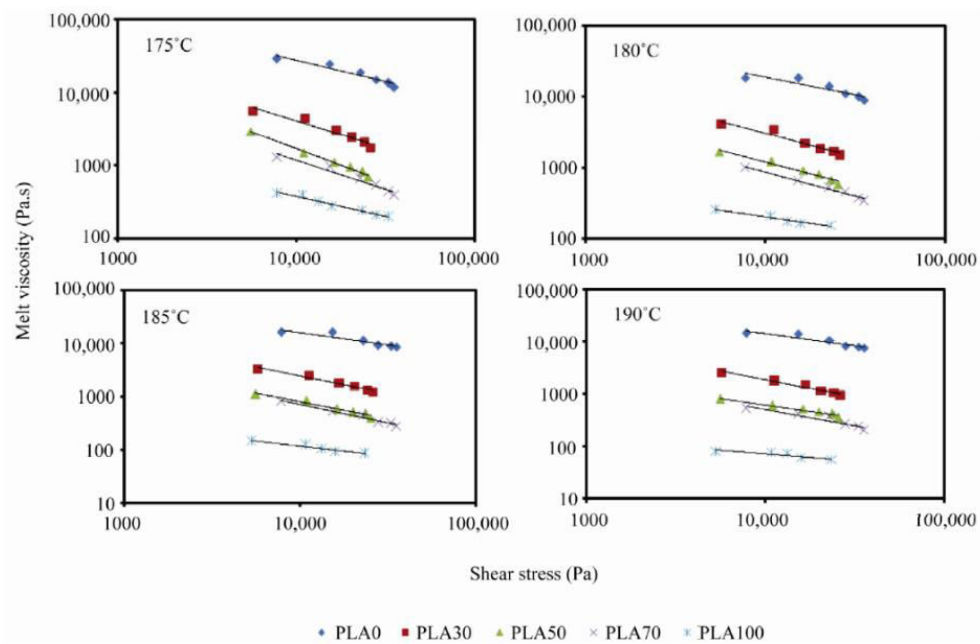

Figure 5: Melt Viscosity vs. Shear Stress for PLA/LDPE Blends [4]

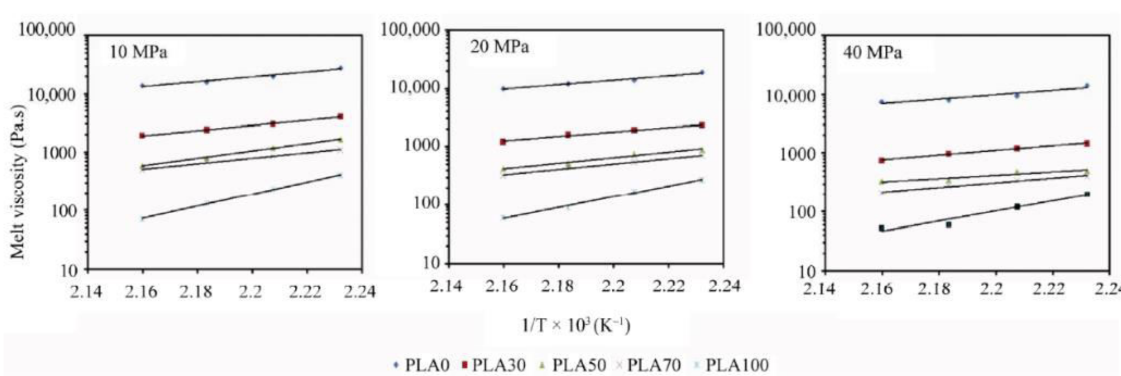

Figure 6: True Viscosity versus 1/T for PLA Samples [4]

To create pellets small enough to flow through the auger bit, a grinder was used to grind pellets to about 1mm in diameter. The screw channel in the auger is only 2mm x 6mm and standard pellets are 3mm pellets in diameter which is too large to flow down. On the finest setting of the grinder, the pellets were able to get to roughly 1mm in diameter which is small enough to flow through the opening.

By slowly heating up an aluminum plate filled with PLA pellets and using a k-type thermocouple to measure the temperature, we estimated the beginning and final stages of melting. The results of this experiment showed that the PLA began melting around 150-160C and fully melted around 180C.

2. DESIGN OF A SCREW EXTRUDER

A small plastic funnel 3D printed funnel attached to the extruder stores the ground up pellet. Optical sensors are used to detect when the hoper is filled or empty. One sensor is placed at the top of the funnel and one is at the bottom. These sensors are used along with the mechanical valve at the pellet inlet. The mechanical valve opens when the funnel is empty and closes when it is full. The valve is actuated using a servo motor and a 3D printed valve cover. A stepper motor directly drives an auger bit to transport the pellets from the funnel into a heated chamber. The heated chamber is comprised of a stainless steel barrel which is insulated with PTFE and threaded into an aluminum heater block. In the heater block is a thermistor and a 12V 40W heater. The thermistor provides feedback for the temperature at the outlet. The heater block conducts heats up the barrel and auger which melts the material. The rotation of the auger adds pressure onto the liquefied plastic, forcing the material through the opening in the nozzle which is 0.4mm in diameter. The nozzle is threaded into the heater block at the bottom.

Table 2: Components Used on Initial Design

Arduino Mega 2560	0.25” Auger Bit	Stainless Steel Barrel
Ramps 1.4 Board	Funnel/Motor Mount	0.4mm Nozzle
A4988 Stepper Driver	40mm Heat Sink	3/8” Inlet Adapter
Nema17 Stepper Motor	40mm Fan	PLA Pellets
12V Heater	Aluminum Heater Core	3/8in Nylon Tube
2x QRD1114 Phototransistor	Submicro Servo Motor	Valve Cover
A4988A Heat Sink	Thermistor Washer	Large Funnel
Aluminum 5mm - 0.25” Shaft Coupler	100k Thermistor	PTFE Tube

2.1 System Design

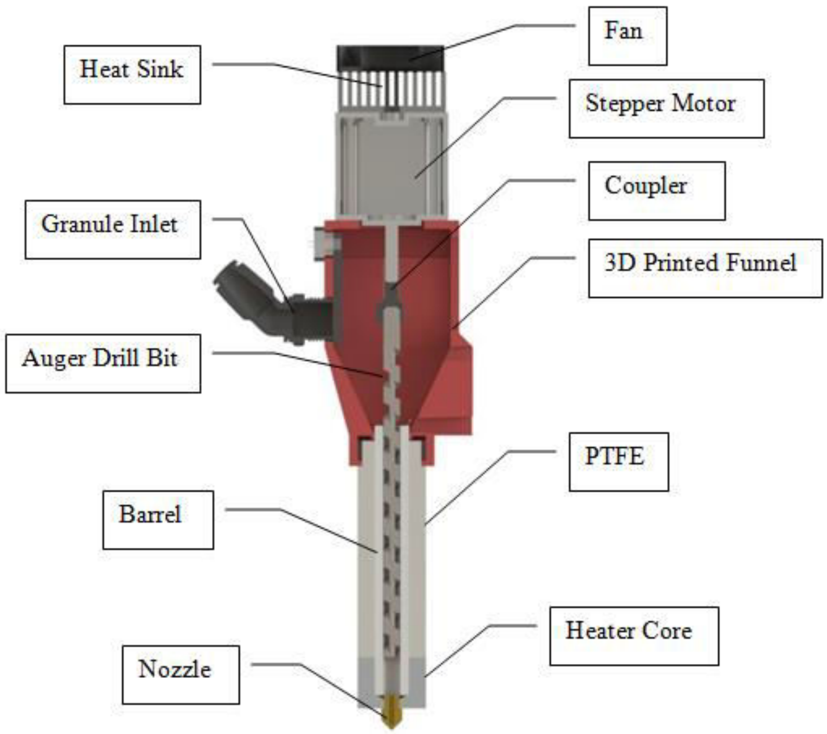

Figure 7: Cross Section of Initial Design

2.2.1 Screw Design and Analysis

We wanted to use off –the-shelf components for the small scale screw extruder. By looking at screw extruders on the market at this scale, we can get an understanding of the L/D ratio needed for our process. The L/D ratio depends on the material used and the expected inlet and output flow rate, however modeling after pre-existing designs is a good place to start. Brabender CWB is a company specializing in screw extrusion for a variety of different materials. For their small scale screw extruder with 0.5 inch diameter, they have a compression ratio of 1:1 up to 5:1 along the screw with an L/D ratio of 10:1 up to 30:1. We found an off-the-shelf auger with an L/D ratio of 18:1 and compression ratio of 1:1. Dimensions for this auger can be seen below.

Table 3: Auger Dimensions

L	Total length of the auger	129 mm
l	Height of the helix	114 mm
w	Width of the spiral cutout	2 mm
h	Height of the spiral cutout	6 mm
rev	Number of helix revolutions	9
P	Pitch	11.56mm
D	Diameter of the screw	0.25in
H	Channel depth height	2 mm
ϕ	Helix angle	45^{o}

2.2 Electro-Mechanical Diagram

The electrical components that were used included two phototransistors, a thermistor, a heater, a servo and a stepper motor.

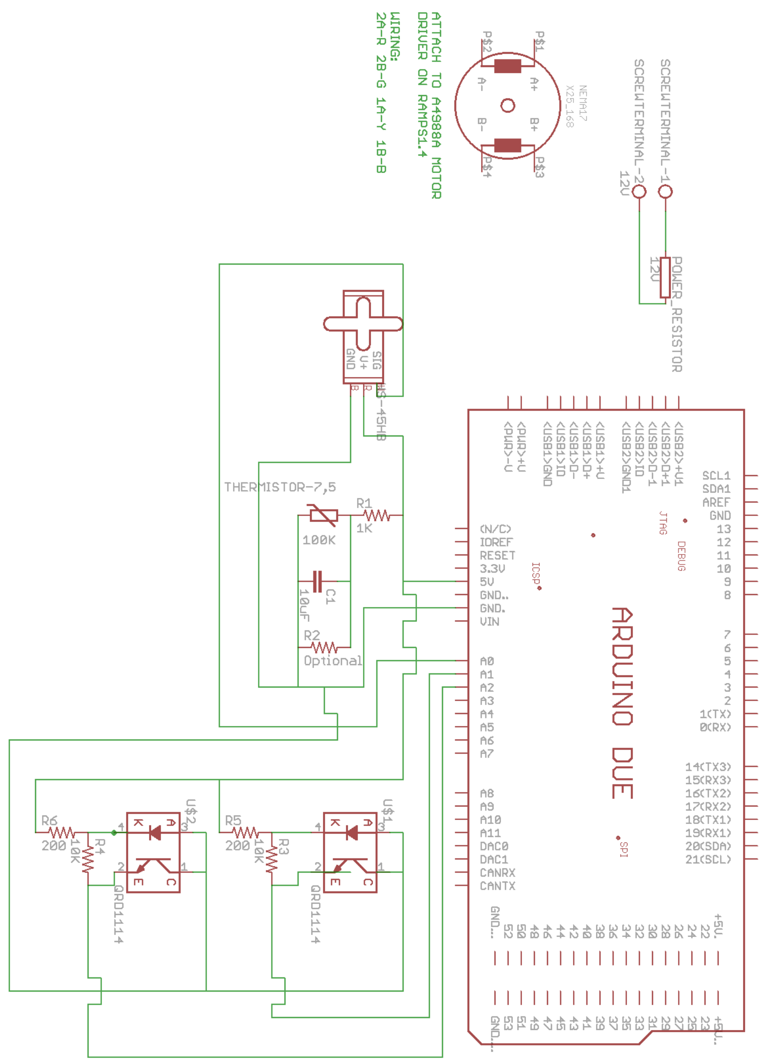

Figure 8: Electro-Mechanical Diagram of Initial Design

Note: Components are attached to Ramps 1.4 board
Arduino Mega 2560 has the same form factor as the Arduino Due

2.3.1 Motor Driver

To drive the screw extruder, a stepper motor is driven from an A4988A motor driver. Each motor driver gets hot therefore it is recommended to glue heatsinks on top of the IC's. We must also set the current limit for the stepper motor driver. Each motor driver also uses a trimpots to adjust the current limit for the motor. Turning the trimpot clockwise will increase the current and counterclockwise will decrease the current. Since our motor is rated with a motor current of 1.2A, if we would like to run the motor without getting too hot, running it at 1A should be sufficient. Since stepper motors have 2 coils, the current through each coil should be 0.5A. The coil current should be less than the trip current for the motor drivers. For the A4988A motor driver, the current limit is $I_{limit}= V_{ref}*2.5$. Solving for V_{ref} gives $V_{ref}= 0.2V$. Now that the limit is known, we can use a screw driver to rotate the potentiometer on the top of the motor driver until the V_{ref} is at 0.2V. This is a good way to make sure we are not over driving the motors.

2.3.2 Thermistor Calibration

The RAMPS 1.4 board has integrated a thermistor circuit (Appendix) that allows users to plug thermistors into the board for temperature measurements. However, this does not give us high resolution near the melting point of PLA. If we create a voltage divider that was linearized about the melting point for PLA, we will have a much higher resolution around the point we are interested in. Therefore, we will not be using T0, T1, and T2 on the Ramps 1.4 board. We will be using analog inputs instead.

Based on experimental tests, the material fully melted around 180C. Since our heater will most likely be higher than the melting point, we will linearize about a higher temperature. To have a linear profile in our range, we must choose R_{load} to be around this temperature. The data sheet for the thermistor gives the resistance values for a given temperature and we can use this information for R_{load}. Choosing 550 Ω with an input voltage of 5V, we have

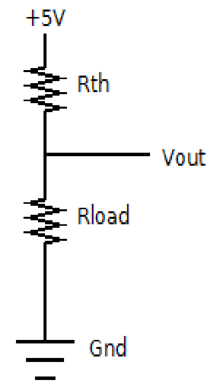

Figure 9: Thermistor Voltage Divider

$$V_{out} = V_{in} * \frac{R_{load}}{R_{load} + R_{therrm}} = 5V * \frac{550\Omega}{550\Omega + R_{therrm}} \tag{2.1}$$

Substituting the resistance values from the thermistor datasheet for 180C and 220C into R_{therm} , we can estimate V_{out} for each temperature. This can be used to find a rough linear estimation for the resolution of the thermistors around the melting point.

Based on the output voltage, the total range of voltage around the melting point is 3.07-2.13 = 0.94V over a 40C range. We know there are 4.88mV per bit from the Arduino microcontroller so we can derive the approximate resolution as follows:

$$\frac{940mV}{4.88\frac{mV}{bit}} = 193bits \quad \text{and} \quad \frac{40C}{193bits} = 0.21\frac{C}{bit}.$$

By dividing the temperature output from the thermistor within this 40C range, we can estimate what we should expect as an output ADC for each temperature

Table 4: Values Close to PLA Melting Point

Temp (C)	R_{load} (Ω)	V_{out}	ADC
180	832	2.13V	857
200	553	2.62V	952
220	379	3.07V	1047

2.3 Screw Extruder Assembly and Maintenance

1) Thread nozzle and stainless steel barrel into heater cartridge
2) Thread barrel into PTFE
3) Align 3D printed funnel with PTFE grooves and screw 2 x 4-40 screws to attach them
4) Thread the granule inlet into the 3d printed funnel
5) Attach valve cover to servo horn
6) Slide servo horn through servo opening in 3D printed funnel
7) Attach servo motor to the 3d printed funnel using two screws
8) Attach shaft coupler to motor and auger bit
9) Use 4 long M3 screws to attach fan to heatsink to stepper motor to 3d printed funnel
10) Insert phototransistors into 3d printed funnel

To clean the barrel, heat up the 12V heater and use cue tip or object with an abrasive surface to clean out viscous liquid. While heated, use a brass brush to clean off the nozzle tip and thin brass wire to clear out nozzle opening. If there is no extrusion, increase temperature to lower viscosity. Make sure the current to the stepper motors is set to the correct level by adjusting the trimpots.

2.4 Results

This resulted in a mechanically sound extruder with sufficient inlet flow and consistent output flow. The system was able to detect granule levels using the optical sensors. Optical sensors depend widely on the environment tested in and the material used therefore was not a robust approach to maintaining inlet flow. The control of the inlet worked well allowing pellets to flow when granule levels were detected. The system was run open loop for an initial proof of concept. The extruder was capable of extruding relatively consistently open loop. For better control of the flow, controls needed to be implemented. If our aim is to improve print speed, having this large of an extruder was not the answer. Reducing the size of the extruder will help improve the speed of the 3d print when implemented onto a 3d printer frame. Although the system worked, it needed improvements to be small and quick when implemented on a 3D printer.

3. SMALL SCALE SCREW EXTRUDER

Results from the initial screw extruder design led to a new design concept. In order to print parts at a high speed, the extruder must be very small to move quickly without pellets jamming at the inlet or along the barrel. The updated extruder design accounts for these changes.

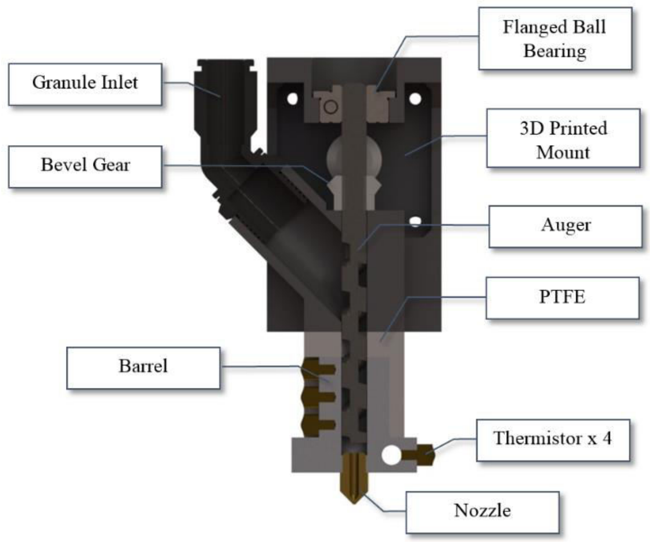

Figure 10: New Design of Screw Extruder

The results from the previous design showed that a majority of the auger bit was used for transportation of the pellets rather than melted material. By reducing the length of the auger , the overall weight and size of the extruder was reduced allowing it to move much quicker when implemented on a 3D printer. The previous design had an L/D ratio of 18:1 and the updated L/D ratio is now 10:1, at the lower limit of the extruders used by Brabender CWB.

The previous design used a long stainless steel barrel which was threaded into the heater core. Heat transporting along the barrel was the main contributor towards liquefying the PLA pellets. By making the heater core and aluminum barrel to be one part, assembly is easier and better heat conduction for liquefying the polymer.

On the previous design, the pellet inlet control actuated by a servo was attached directly on the extruder which added unnecessary weight. The new design controls the granule inlet separate from the extruder itself. A servo is used to open or close the flow at the inlet in a similar way, except the flow is controlled on the tubing away from the extruder rather than on the extruder. A servo controls a plunger that slides along a slot to open and close the valve. The length of the slot was determined by $x=r*\cos(\theta)$ for a changing r. By setting the servo motor to 60 degrees as closed, 30 degrees is open, and the maximum radius for the slot as 0.6 in, we can determine x which is the length of the slot needed to open and close the valve. However, further discussion led us to determine that the control of the inlet flow was unnecessary with the correct inlet angle but may be explored further on future design iterations.

Previously, a single thermistor was used to detect the temperature of the heater. This gave us a sense of the temperature at the outlet, but not the temperature during the melting process. We would also like to know the position at which the material fully melts to a liquid state. By stabilizing this position and maintaining consistent inlet flow, our output flow should be consistent. That is why the new design has a thermistor array; to detect the temperature along the barrel as the granules turn from solid to liquid phase. This will give us sensory feedback for the temperature at discrete points along the barrel allowing us to approximately detect the position at which the material melts. For the updated design, there were four thermistors: one to directly measure the temperature of the heater and three for the barrel. Because the thermistors are threaded, the thermistor was used as a set screw to hold the heater in place. This ensures that the temperature measurement is a direct measurement. The three thermistors along the barrel allow for temperatures to be measured at the bottom, middle and top of the barrel to give feedback as to how the temperature is propagating along the barrel.

3.1 Output Flow Rate Model

Assuming the viscosity of the material is constant along the barrel and the screw speed is constant, we can model the output flow rate in m^3/s for the isothermal case by

$$Q = P * \frac{Fbd^3}{12\eta L_d} \tag{3.1}$$

modeling the flow based on channel geometry [6].

Table 5: Extrusion Variable Definitions

Q	Output flow rate (m^3/s)
P	Output Pressure (Pa)
F	Flow coefficient
L_d	Length of Barrel (m)
b	Channel width (m)
d	Channel height (m)
η	$m(^oC)*\gamma^{n-1}$
m	Consistency index function of T
n	Power Law
γ	Viscosity (Pa.s)
Q_d	Drag flow (m^3/s) (Q_{max})
Q_p	Pressure flow
D	Diameter of the screw (m)
N	Screw revolution (rpm)
H	Channel depth of the screw (m)

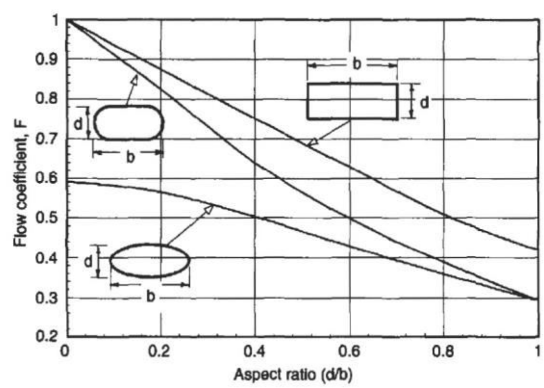

Figure 11: Flow coefficient for a given channel geometry [Crawford(2,p.269)]

ϕ	Helix angle of screw (degree)
L	Length of the screw (m)

The flow coefficient can be determined using the channel geometry. We can then use the operating pressure in Pa for the output for the isothermal case as

$$P = \frac{2\pi\eta D^2 NH \sin(\phi)\cos(\phi)}{\frac{1}{3Ld}(\frac{Fbd^3}{\pi} + DH^3 \sin^2(\phi))} \tag{3.2}$$

This can be used to determine the output flow rate as a function of the drag flow and pressure flow.

$$Q = 0.5\pi^2 D^2 NH \sin\phi \cos\phi - \frac{\pi DH^3 \sin^2 \phi P}{12\eta L} \tag{3.3}$$

$$Q = Q_d - Q_p$$

Using the parameters from the design, we can develop an equation for the flow rate that is dependent on the screw.

Table 6: New Auger Dimensions

L	Total length of the auger	98.6 mm
l	Height of the helix	63.5 mm

w	Width of the spiral cutout	2 mm
h	Height of the spiral cutout	6 mm
rev	Number of helix revolutions	3.5
P	Pitch	16.66mm
D	Diameter of the screw	0.25in
H	Channel depth height	2 mm
ϕ	Helix angle	45^{o}

$$Q = 0.5 * \pi^2 * (.00635m)^2 * N * .002m * \sin(45)\cos(45) - \frac{\pi * .00635m * (.002m)^3 \sin^2(45) * P}{12 * \eta * .0635m}$$

$$Q = 1.9898 * 10^{-7} * N - 1.0472 * 10^{-10} * \frac{P}{\eta}$$

3.2 Max Output Pressure

When there is a high pressure drop at the output of the extruder, Q becomes equal to zero meaning the drag flow equals the pressure flow. This is the point at which the material will stop extruding because of too much built up pressure. This pressure is useful because it is the point when the extruder will stop extruding.

$$P_{max} = \frac{6\pi DLN\eta}{H^2 \tan(\varphi)} \quad (3.4)$$

$$\tan(\varphi) = 0.2/0.25 = 0.8$$

$$P_{max} = \frac{6\pi * .0635\text{m}.00635\text{m} * N * \mu}{(.002)^2 \tan(45)} = 29923.7 * N * \eta$$

3.4 Flow Rate Output based on Screw Speed and Temperature

We would like to know the relationship between the screw speed and the output flow rate. This relationship can be determined experimentally. By extruding over a period of time, we can measure the mass of the material at the output at different screw speeds and different temperatures. This will give us a direct relation between the screw speed, temperature, and output mass flow rate. Since $V=m/\rho$ and with a known density, we can find the volume of the extruded material and the volumetric flow rate.

By extruding over a certain time, we can weigh the extruded material to find the different flow rates. Given that the density of the material is $1.32 g/cm^3$, we can determine the rate of extrusion for each test

Table 7: Screw speed to extrusion rate relationship

Screw Speed (RPS)	Temperature (C)	Mass Flow Rate Trial 1 (mg/sec)	Rate of Extrusion Trial 1 (mm/sec)	Mass Flow Rate Trial 2 (mg/sec)	Rate of Extrusion Trial 2 (mm/sec)
1	180	0.75	6.64	0.806	7.14
2		0.7	6.20	0.583	5.17
3		0.283	2.51	0.2	1.77
1	190	0.3	2.66	0.233	2.06
2		0.25	2.14	0.35	3.10
3		0.2	1.77	0.1833	1.62
1	200	0.117	1.04	0.233	2.06
2		0.333	2.95	0.117	1.12
3		0.27	2.39	0.133	1.18

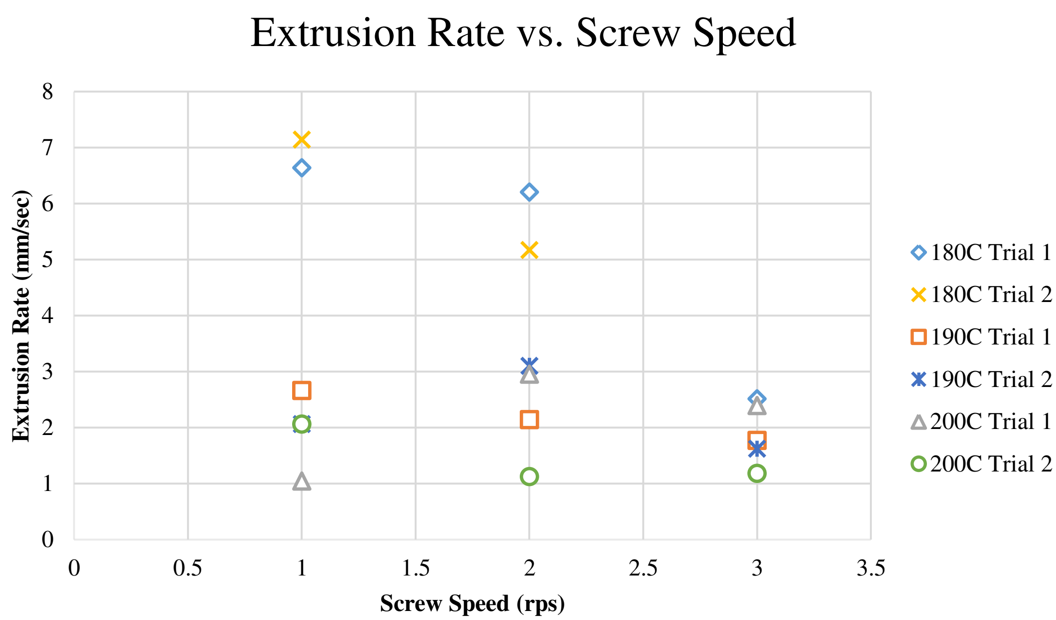

Figure 12: Plot of Extrusion Rate vs. Screw Speed

Standard FDM extruders run at 60-90 mm/min for 1.75mm filament at the inlet which is 1-1.5mm/s. By converting this input extrusion to the output for the diameter of the nozzle we are using (assuming a 1:1 relation between inlet and outlet), we can determine how close we are to extruding at the speed of a standard FDM extruder. The volume of the inlet should equal the volume at the outlet. By using 1.25mm/sec, we are achieving volumetric flow rate around 3mm^3/sec with standard FDM extruders. This corresponds to an extrusion rate of 35.15 mm/sec.

By running the extruder with step variations in the temperature for 180, 190, and 200 C, we can analyze what happens during the transition between temperature changes. Each of these tests are performed with a constant screw speed. We are concerned with how the temperature of the heater responds to changes.

Table 8: Stepping temperature at constant screw speed

Screw Speed (RPS)	Temperature (C)
1	180
	190
	200
2	180
	190
	200
3	180
	190
	200

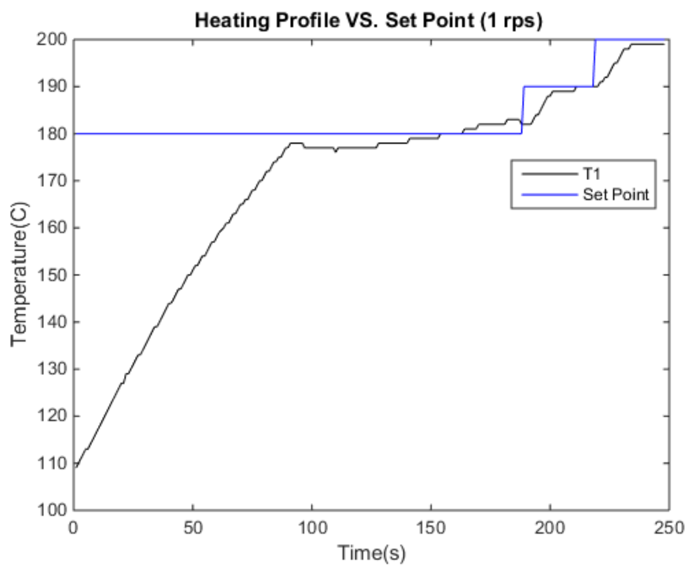

Figure 13: Step Response Varying Temperature Constant Speed (1 rps)

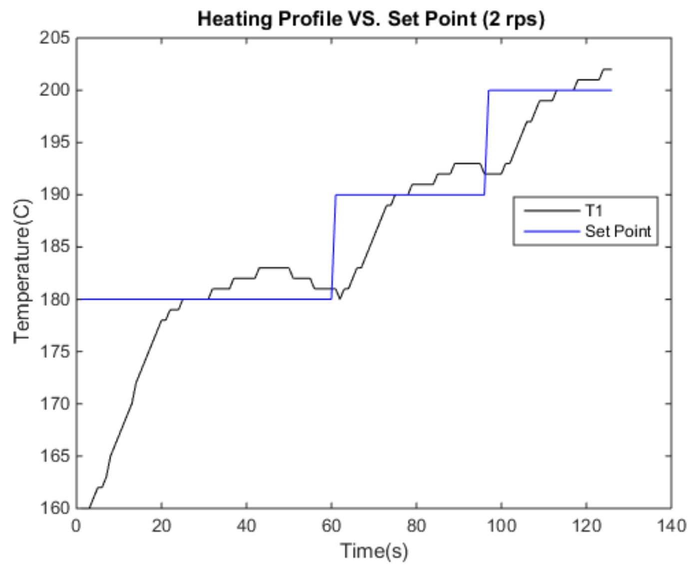

Figure 14: Step Response Varying Temperature Constant Speed (2 rps)

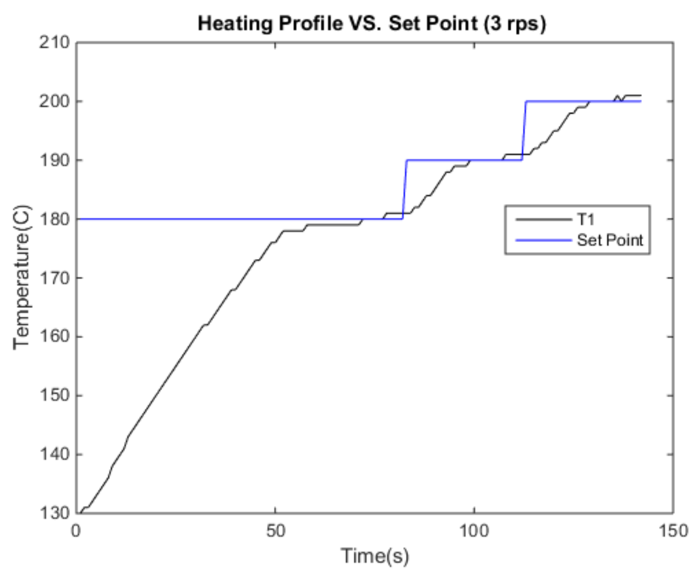

Figure 15: Step Response Varying Temperature Constant Speed (3 rps)

We will repeat the same process except stepping the screw speed and keeping constant temperate instead. This will show how the system will respond to changing the screw speed. The dotted vertical lines indicate a change in screw speed. While the system was heating up, there was no extrusion

Table 9: Stepping screw speed with constant temperature

Screw Speed (RPS)	Temperature (C)
1	180
2	
3	
1	190
2	
3	
1	200
2	
3	

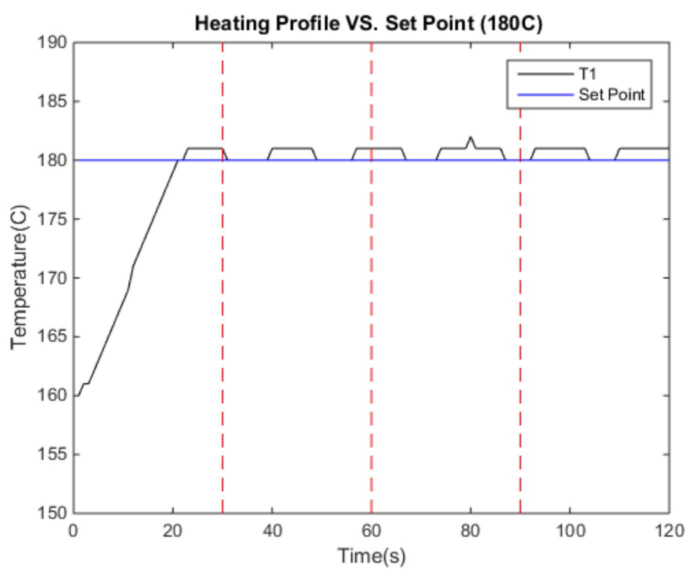

Figure 16: Step Response Varying Screw Speed Constant Temperature (180 C)

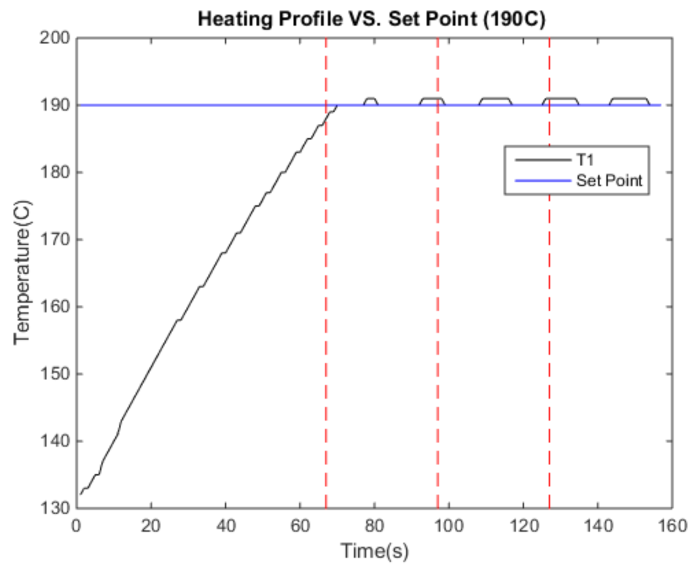

Figure 17: Step Response Varying Screw Speed Constant Temperature (190 C)

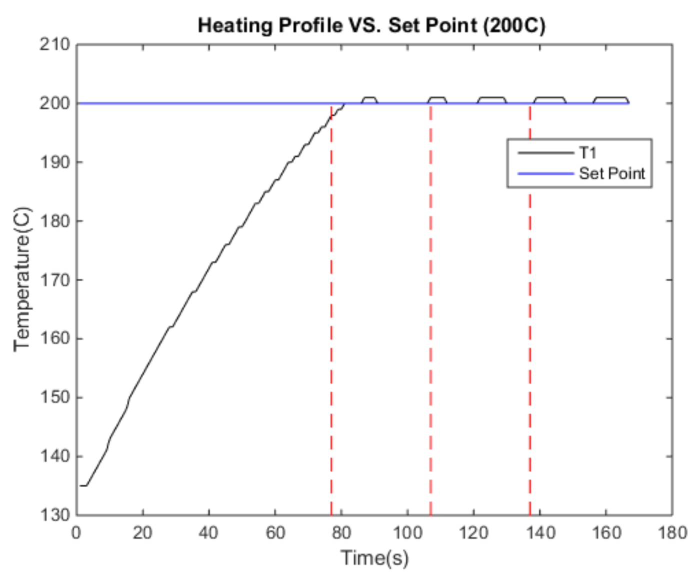

Figure 18: Step Response Varying Screw Speed Constant Temperature (200 C)

These results show the effects that varying the screw speed and temperature have on the system. However, by changing voltage input to the heater at different levels, you can have more control over how the system responds. The above step response plots indicate how the system responds to immediate changes in screw speed and temperature but for bang-bang control using feedback from the heater thermistor.

4. SOFTWARE

In order to 3D print an object, you must create a digital three-dimensional file using CAD software and convert it into an STL file format. This file format represents the outer surface geometry of the three dimensional part. A slicing program such as Slicer can then be used to create the toolpath for the extruder. It slices the three dimensional part into layers. The firmware and host software are then used to control the extrusion process and movement of the gantry to follow the toolpaths from the STL file. Control of the 3D printer is written in a format called G-code. This code allows the printer to intake caned commands and execute these commands.

5.1 Firmware

Arduino was used to test the screw extruder to understand its characteristics such as output flow rate for given inputs. The code was written in a modular fashion to test the capabilities of the extruder by creating functions for each part of the extrusion process. By using bang-bang, we can control the temperature of the extruder. Each temperature was linearly interpolated from a table of known values which compares the output from the thermistor to the actual temperature. The stepper motor is run open loop. It can either be ran continuously at a specific speed (in rotations per second) or for a specific amount of steps at a specific screw speed. Combining the motor and temperature control, we are able to test the capabilities of the screw extruder. This code can be seen in the Appendix.

When implementing the extruder onto an actual 3d printer frame, one possibility for the firmware is to use the open-source software Marlin. Marlin is commonly used for 3D printers because of the available resources and community around developing this software. The design of the software makes it relatively simple to modify parameters according to your specific printer. There are other options such as Repetier firmware as well. The benefit of using Marlin is the wide open-source community available for debugging common errors with the firmware and along with continuous advancements from those who use it.

5.2 Host Software

The host software is the interface that is used to control and display parameters on the firmware along with other adjustments such as object orientation and placement. These parameters are important because the orientation of the part affect the structural integrity along with the dimensional tolerances of the final printed part. Repetier also provides visual depiction for the temperature as it propagates in time, an interface where G-code can be implemented and fine tuning print settings. One software that can be used for the 3D printer is Repetier host software. Repetier is compatible with Marlin and other firmware and is open-source.

5. FUTURE CONSIDERATIONS

There are changes to the current design and alternative options that could improve its current state.

Dimensioning the screw extruder properly can optimize the speed that each part can be printed and extruder at. The screw can be designed with complex geometry to account for transition, mixing and compression phases during extrusion. There could also be maintenance improvements and design changes for modularity to make assembly and disassembly easier. Although increasing the size of the screw would make a bigger extruder, if we used the 5/8 inch diameter auger, we would be able to skip the step of grinding pellets and extrude directly from the pellets.

The material that the extruder mount was made from could have a higher temperature. Because of the high temperatures, 3d printing with a material with a higher melting point would prevent warping near the parts that are being heated. Heat propagating up the screws that are holding the extruder together cause the material to warp. By using a 3d printed mount with a higher melting temperature, the mount will less likely to warp which would increase the lifespan of the extruder.

The placement of the heater could also be changed. A heater coil or multiple heaters could be used to better control over the heat distribution along the barrel. Although the initial design was changed, there could also be continuing improvements on the initial design concept.

The material being extruded can also be adjusted. By using room temperature fluid or polycaprolacton, we could test the pressure in the system and see the effects of the rotation of the auger without the effects of the heater. We could then use clear heat resistant tube to observe the flow of the material as the auger rotates. Another option would be to find pellets that are small enough to flow down the auger rather than grinding them ourselves. Some material and pre-ground pellets can be found at companies such as Midwest Elastomers which would get rid of the grinding process.

Measuring pressure and flow at the output would give great feedback that we could utilize to control the output flow, however, it is difficult to implement. Pressure sensors must be able to withstand high temperature, small in dimension and measure small pressure changes. These restraints make the pressure sensors expensive. Air compression can also be added to the system to improve and control the inlet flow. Sensors could also be used to determine the pressure using a correlation between the measured back pressure from the auger and the output pressure. You could also measure the distance that a spring deflects to determine the back pressure from the auger. Flow sensors are difficult to implement since it must be in line with the flow of material and must be able to withstand high temperature at nozzle. A pellet counter can be used to detect when granules enter funnel for the initial design. A faded grid on the side of the shaft coupler for the initial design coupled with a phototransistor can be used to detect changes in how much the funnel is filled. A solenoid could be used to stop inlet flow of granules when sensor detects material.

By using the screw speed and temperature data and analysis performed either, we will be able to model the system and use different control techniques for the system. The model obtained from the steady state analysis is valid around the operating point. However, the key to modeling the system is to use system identification tools to analyze the transient when varying the screw speed with constant temperature from one steady state to another and vice versa. The transient behavior is necessary for the development of efficient feedback control laws.

6. CONCLUSION

The developments in 3D printing have led to the production of objects made from materials such as plastic, metal, paper and even food. This has given end users the opportunity to explore their creativity. 3D printing is being used by universities, manufacturing companies, and everyday users as a quick method of prototyping designs, exploring the capabilities of this technology and seeking ways to improve it. Because of the quick emergence of this technology, leaps have been made towards improving manufacturing.

The development of screw extrusion as an alternative 3d printing process will hopefully open doors to new ideas for 3d printing. Screw extrusion will allow users to have access to a wider variety of materials with a high resolution for their 3d printed parts.

APPENDIX

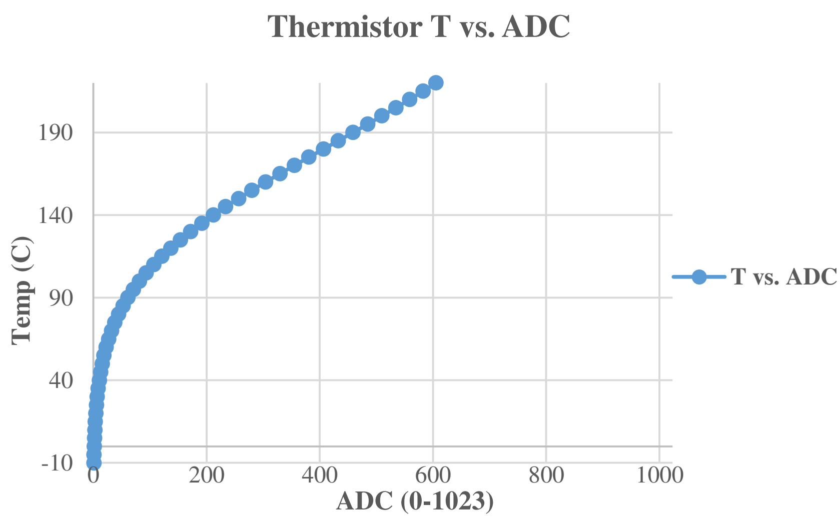

Figure 19: Thermistor Plot T vs. ADC

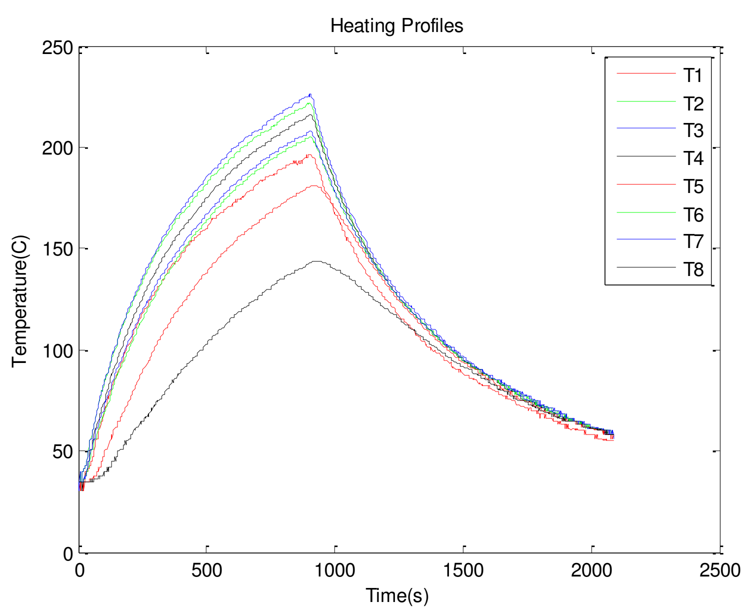

Figure 20: Measured temperature profiles for 8 thermistors heating and cooling at 60 percent constant heat.

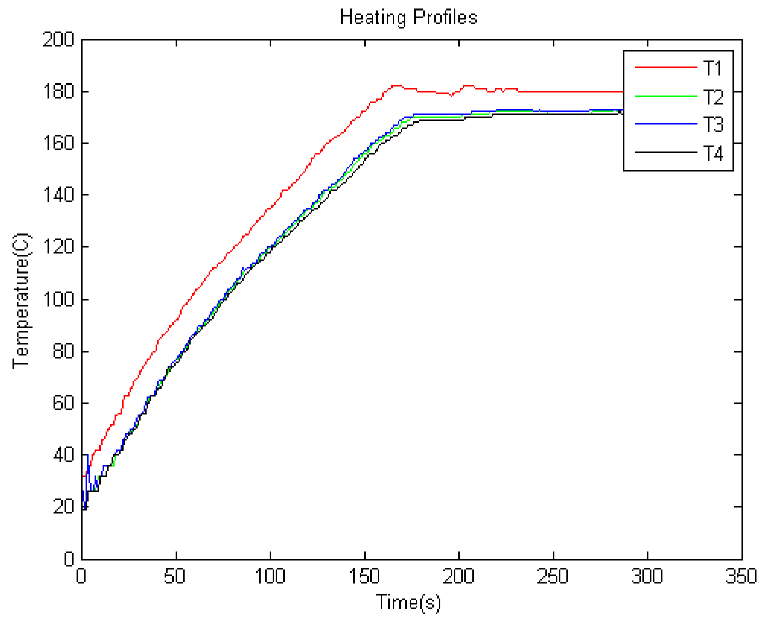

Figure 21: Temperature profiles for 4 thermistors heating at 100 percent constant heat until 180C was reached at the nozzle then 40 percent power.

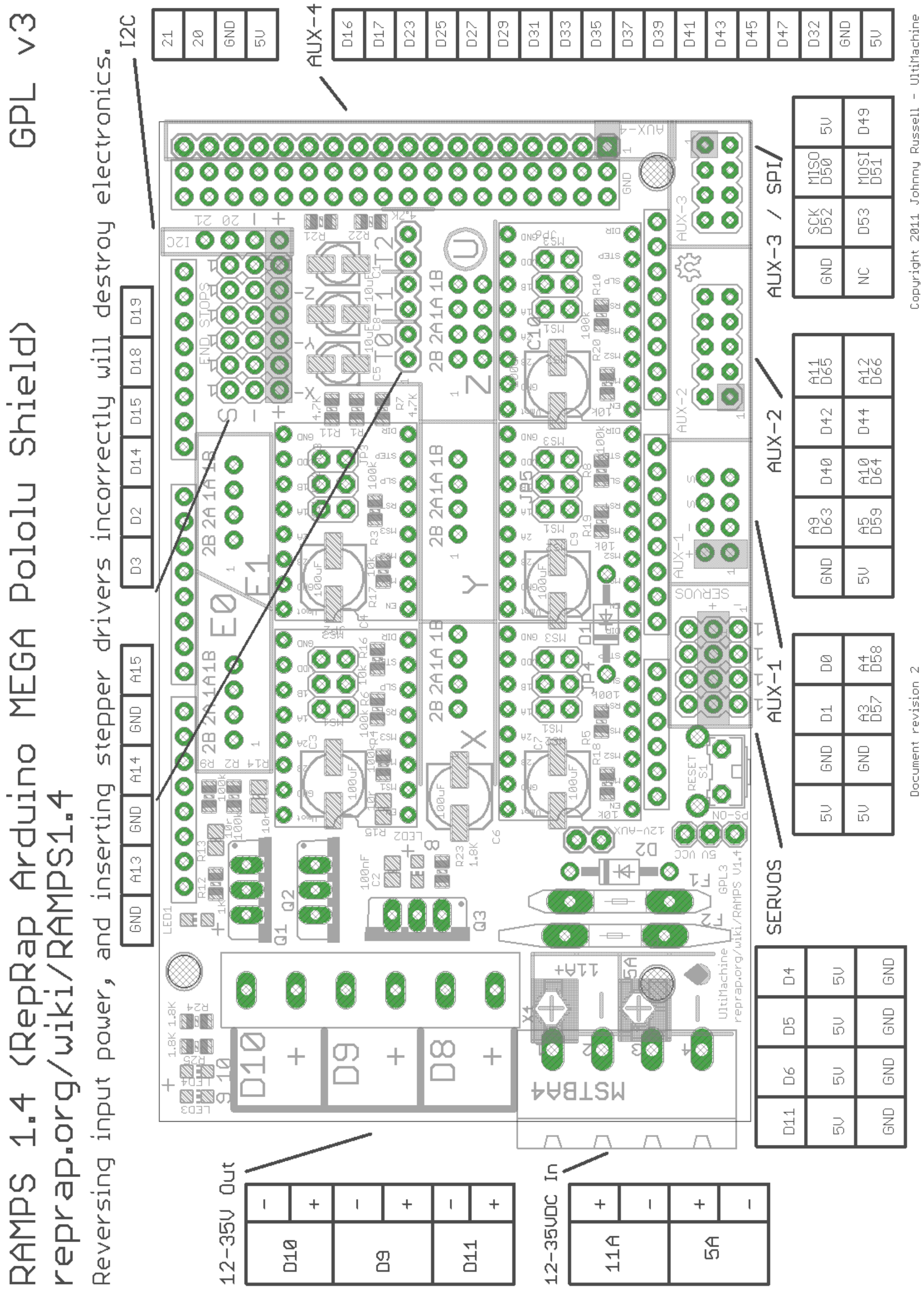

Figure 22: RAMPS 1.4 Pin Out Diagram

Table 10: Open Loop Code for Control of a Screw Extruder

```
/* OPEN LOOP TEMPERATURE
CONTROL /*
 -Regulate temperature using Bang-Bang
 */
#include <TimerThree.h>
#include <superSerial.h>
#include <math.h>

#define T1Pin A3
#define T2Pin A4
#define T3Pin A5
#define T4Pin A10

#define heatPin 10

#define EstepPin 26//36
#define EdirPin 28//34
#define EenablePin 24//30
#define LED 13
#define fanPin 9

int steps;
float delayy;
int i = 0;

long previousMillis = 0;
long interval = 1;
float time;
float previousMotorDelay = 0;
int Estate = LOW;

int rawT1, rawT2, rawT3, rawT4; //
Integer ADC value
int T1, T2, T3, T4;

#define numTemps 61// number of rows
on the table below
short temptable[numTemps][2] = {
  { 856 , 300 },
  { 846 , 295 },
  { 836 , 290 },
  { 825 , 285 },
  { 813 , 280 },
{ 773 , 265 },
  { 758 , 260 },
  { 742 , 255 },
  { 725 , 250 },
  { 707 , 245 },
  { 689 , 240 },
  { 669 , 235 },
  { 649 , 230 },
  { 628 , 225 },
  { 606 , 220 },
  { 583 , 215 },
  { 559 , 210 },
  { 535 , 205 },
  { 510 , 200 },
  { 485 , 195 },
  { 459 , 190 },
  { 433 , 185 },
  { 407 , 180 },
  { 381 , 175 },
  { 355 , 170 },
  { 330 , 165 },
  { 305 , 160 },
  { 280 , 155 },
  { 257 , 150 },
  { 234 , 145 },
  { 212 , 140 },
  { 192 , 135 },
  { 172 , 130 },
  { 154 , 125 },
  { 137 , 120 },
  { 121 , 115 },
  { 107 , 110 },
  { 94 , 105 },
  { 82 , 100 },
  { 71 , 95 },
  { 61 , 90 },
  { 53 , 85 },
  { 45 , 80 },
  { 38 , 75 },
  { 32 , 70 },
  { 27 , 65 },
  { 23 , 60 },
  { 19 , 55 },
```

```
  { 800 , 275 },
  { 787 , 270 },

  { 11 , 40 },
  { 9 , 35 },
  { 7 , 30 },
  { 6 , 25 },
  { 4 , 20 },
  { 4 , 15 },
  { 3 , 10 },
  { 2 , 5 },
  { 2 , 0 }
};

void setup()
{
  Serial.begin(9600);
  pinMode(EstepPin, OUTPUT);
  pinMode(EdirPin, OUTPUT);
  pinMode(EenablePin, OUTPUT);
  pinMode(fanPin, OUTPUT);
  pinMode(LED, OUTPUT);
  pinMode(heatPin, OUTPUT);

  digitalWrite(EenablePin, HIGH); //off
  digitalWrite(LED, LOW);
  analogWrite(heatPin, 0);

  Timer3.initialize(1 * 1000000); //time
inbetween high and low for printing
  Timer3.attachInterrupt(printstuff); //print
stuff to serial port is on timer 3
}

//volatile unsigned long blinkCount = 0; //
use volatile for shared variables

void loop()
{
  //analogWrite(heatPin, 100);//26, 52, 77,
102, 128

  if (T1 <= 175) {
    analogWrite(heatPin, 255);//255
    digitalWrite(EenablePin, HIGH); //off
  { 16 , 50 },
  { 13 , 45 },

    Extrude1(1);

    if (T1 > 175 && T1 <= 180) {
      analogWrite(heatPin, 130)  ;//87/255:
84
    }

    //analogWrite(fanPin, 50);//185
    //Extrude2(0.25,1);//0.5,1
    if (T1 > 180) {//188
      analogWrite(heatPin, 50)  ;
    }
  }




  //Ask();
}

void Extrude1(float rps1)
{
  /*
   Motor: 200 steps/rev 3200
microsteps/rev

   3200steps/rev *.5rev/sec =1600steps/sec
   1/1600 sec/step*1000000=312
microsecs/step
   */
  delayy = 1000000 / (3200 * rps1); //312;
  delayy = delayy / 2; //2 delays for
stepping

  digitalWrite(LED, HIGH);
  digitalWrite(EenablePin, LOW); //on
  digitalWrite(EdirPin, HIGH);

  digitalWrite(EstepPin, HIGH);
  delayMicroseconds(delayy);
  digitalWrite(EstepPin, LOW);
  delayMicroseconds(delayy);
```

```
  }
  if (T1 > 175 && T1 <= 185) {
}


void Extrude2(float rps2, int rotations)
{
  /*
   Motor: 200 steps/rev 3200
microsteps/rev

   3200steps/rev *.5rev/sec =1600steps/sec
   1/1600 sec/step*1000000=312
microsecs/step
   */
  delayy = 1000000 / (3200 * rps2); //312;

  delayy = delayy / 2; //2 delays for
stepping
  steps = abs(3200 * rotations); //3200*1;
  digitalWrite(LED, HIGH);

  digitalWrite(EenablePin, LOW); //on
  digitalWrite(EdirPin, HIGH);
  for (int i = 0; i < steps; i++)
  {
    digitalWrite(EstepPin, HIGH);
    delayMicroseconds(delayy);
    digitalWrite(EstepPin, LOW);
    delayMicroseconds(delayy);
  }
}


//  if (e>0) {digitalWrite(EdirPin,LOW);}
//  if (e<0) {digitalWrite(EdirPin,HIGH);}
//
//  e=(int)abs(e); // mm
//  steps = e*stepMM; // theoretical steps
//  int time=e/(int)velocity; //seconds
//  int sec_per_step= time/steps; //min 20
//  delayy = sec_per_step;
//delayy=1;

  rawT3 = analogRead(T3Pin);
```

```
int readTemp(int reading)
{
  int rawtemp = reading;
  int current_celsius;
  byte i;
  for (i = 1; i < numTemps; i++)
  {
    if (temptable[i][0] <= rawtemp)//goes
through left column of table skipping the
first value
    {
      int realtemp  = temptable[i - 1][1] +
(rawtemp - temptable[i - 1][0]) *
(temptable[i][1] - temptable[i - 1][1]) /
(temptable[i][0] - temptable[i - 1][0]);

      // Overflow: clamp to 250 degrees
celsius
      if (realtemp > 250) {
        analogWrite(heatPin, 0);
        Serial.println(" *** TOO HOT! ***
");
      }
      current_celsius = realtemp;
      break;
    }

    if (i == numTemps) {
      current_celsius = 250;
      Serial.println(" *** OVERFLOW ***
");
    }
  }
  return current_celsius;
}


void printstuff()
{
  time = millis() / 1000;

  rawT1 = analogRead(T1Pin);
  rawT2 = analogRead(T2Pin);
```

```
  rawT4 = analogRead(T4Pin);

  T1 = readTemp(rawT1);
  T2 = readTemp(rawT2);
  T3 = readTemp(rawT3);
  T4 = readTemp(rawT4);

  Serial.print(" ");
  Serial.print(T1);
  Serial.print(" ");
  Serial.print(T2);
  Serial.print(" ");
  Serial.print(T3);
  Serial.print(" ");
  Serial.print(T4);
  Serial.print(" ");
  Serial.print((int)time);
  Serial.print(" ");
  Serial.println(rawT1);
}

//  Serial.print(rawT1);
//  Serial.print(" ");
//  Serial.print(rawT2);
//  Serial.print(" ");
//  Serial.print(rawT3);
//  Serial.print(" ");
//  Serial.print(rawT4);
//  Serial.println(" ");


void Ask()
{
  float stepMM = 6.5; // 1/(.02*8)

  Serial.println("How much would you
like to extrude? [mm]");
  Serial.println("Negative for reverse");
  Serial.println("");
  Serial.print("e : ");
  float e = sSerial.readFloat();

  Serial.println("How fast would you like to
go?");
  Serial.println("");
  Serial.print("velocity : ");
  float velocity = sSerial.readFloat();
  Serial.println("");
  Serial.println("");

  Serial.println("Set Points:  ");
  Serial.print("e : ");
  Serial.print(e, 1);
  Serial.print(" mm   ");
  Serial.print("velocity : ");
  Serial.print(velocity, 1);
  Serial.print(" mm/s   ");
  Serial.println("");
  Serial.println("");
  Serial.println("");
  //delay(500);
}
```

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