University of Victoria

Engineering & Computer Science Co-op

FILLER

Electrical Design and Analysis of a PID control for a 3D Filament Recycler Heater

Victoria, BC

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Computer Engineering
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In partial fulfillment of the requirements of the B.Eng. Degree

University of Victoria
Faculty of Engineering

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To:

Dear Ash,

I'm excited to deliver the work and achievements I've made throughout this fall 2021 term doing a personal project of mine that sparks the world of 3D printing and sustainability, the "Electrical Design and Analysis of a PID control system for a Filament Recycler Heater". Most of this work has been a lot of prototyping, market research, and PID bench tests in performance of its main goals for melting reused plastics properly. Factors considered throughout the report are speed, cost, software state analysis implementation and ramp-up times. The report will consist of the entire project design process, problem definition, limitations, and a hardware & software design analysis breaking down the logistics of the electrical heater functionality.

Throughout this course, I've heavily practiced circuit protection, hardware-to-software integration, and unit tests in bettering the overall project solution. As many of my previous coops leaned towards PCB manufacturing, I wanted to gain more experience in integration and programming in ENGR 446. Thank you for your time and I really hope you enjoy my findings!

Regards,

FILLER

Wilson Nguyen, **FILLER**
Computer Engineering 4B Student, Fall 2021

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Executive Summary

This report conducts a design and analysis of a PID control for a 3D filament recycler heater. A 3D filament recycler heater is one of the first steps to building an entire 3D filament recycler, with an importance to reducing plastic waste by reusing 3D plastic material. As 3D printers are used more than ever from hobby to industry use, thousands of plastic filaments are made to provide material to 3D print. However, once a 3D printed object is beyond its rated lifecycle, having a motivation to shred, melt, and re-use that object into a recycled filament roll reduces the production of new filament that may not be needed at all.

Research was conducted upon several types of heaters such as a cast-in, cartridge, immersion, and a coil heater. Based off accessibility, manufacturing time, cost, and power restraints the cartridge heater is implemented in the final solution design. In addition, the heat distributed environment was considered to account for placements of the heater itself and gives a more in depth understanding on how the 3D filament recycler heater functions. With aftermarket research, the screw barrel system allows easy placement of the cartridge heater along with low cost in implementation of the design. In addition, a circuit was designed and implemented with a PID digital control system using an Arduino Uno microcontroller. This allowed both software control state analysis and a hardware integration design process to be tested to validate the PID Control.

The circuit design allowed ramp-up & bench tests to compare amongst two similar hot-end systems while achieving a ramp-up time to the desired PLA melting temperature of 210 ℃ within 2 minutes and 30 seconds. Second, the PID Control produced steeper ramp-up slopes than both compared 3D printer calibrated hot-ends that have similar heater cartridge power specifications while achieving target temperature steady state. Based on these results, the PID Heater solution was deemed successful within the project requirements and performed the main functionality of the MCU PID Control system while reaching the target temperature and well under project costs.

Glossary

Microcontroller	A single integrated circuit that is utilized in performing various tasks. They contain programmable input and output ports, RAM, memory, additional peripherals depending on the MCU.
PLA	Polylactic Acid that is a polymer used in plastic products.
Thermistor	A resister that is heavily dependent with respect to temperature, used to measure the current temperature surrounding the thermistor.
Extruder	A machine, system that allows extrusion to happen, it pushes material through a guide that creates an object.
PID	Proportional, Integral and Derivative.
Steady State	When the desired setpoint is achieved without huge differences from the actual feedback, maintained at setpoint respect to time.

1.0 Introduction

Everyday households to various consumer products are generally made with plastics to and contributes to a huge factor of pollution waste. Amongst plastic usage, 3D printers use plastics to prototype, create, and try out new things for industry or hobby use. As plastics are a heavily used material, an oncoming issue is how to recycle plastic that has been purposed beyond its life cycle. 3D printers are used now more than ever with advanced technology making it easier for the consumer with minimal "3D printing" knowledge. The question remains for left over scrap pieces, broken PLA plastic parts and out of use 3D plastic material that cannot be reused due to its deformed state or end of life cycle. Figure 1 displays an ideal approach in tackling reused printed plastics and repurposed for the user's needs using a 3D filament recycler to change recycled plastic into something useful again [1]. This report will focus on the plastic extrusion stage from Figure 1, more specifically how feasible designing and analyzing a PID control system for a 3D filament recycler heater.

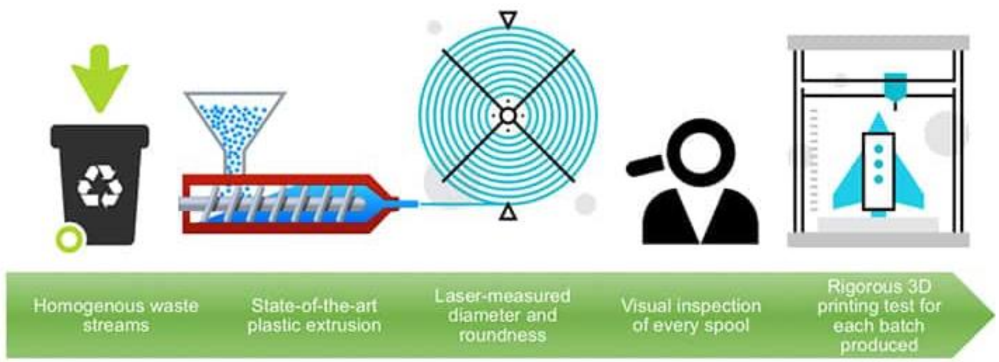

Figure 1 Reused Plastic Streamline for 3D printers [1]

1.1 Problem Overview

As mentioned previously, the main objective of this report is to design and analyze a PID control for a 3D filament recycler heater in aiding as a solution for a sub-part of the 3D filament recycler. The PID heater system comes with many steps, the factors such as the type of plastic properties vary, the forms in how plastics can be recycled (pellets, solids, and powder), the feedback & output system and capacity of plastic that can be accommodated are just a few in tackling this system. To reuse solid plastic, it must go through a heater system to change its form into a malleable phase that is then molded or printed into the user's desire. Finding an efficient PID heat system and optimizing it will achieve feasibility for the specific implementation in a 3D filament recycler heater. This report will contain, comparing similar heater system bench tests, evaluating different heater systems, and designing & prototyping a software-to-hardware PID control system to prove the overall feasibility of the PID closed loop heater system for the 3D filament recycler's application.

1.2 Proportional Integral Derivative

Proportional-Integral-Derivative is known as PID. More specifically, a PID control loop is a system control method for adjusting input continuously to accurately achieve its output while reducing error. Once all proportional, integral, and derivative gains are calculated, the sum of them will be the new input value onto the system to accurately adjust the output.

The proportional gain represents the change between the set target and actual temperature further known as the error [2]. As the proportional gain is increased, the response to change will be increased but can contribute to big temperature jumps and oscillates within a temperature gap relative to the target temperature [3].

The integral accounts for the continuous errors and accounts for settling time once the temperature has been reached. An overshoot, when temperature goes beyond the target temperature can happen a lot and result in oscillation, the integral will account for this room of error based on the average temperature and corrects the system to reach a steady state [4]. A steady state is ideal, as it means the setpoint is consistent and good for the heat system to melt the plastic at the fixed rated temperature. The previous values of the error are considered for this variable and adjusts for long term errors based on its past errors.

The final variable, derivative, assists the "rate of change in error" respect to time and coincides with the proportional gain to account for the oscillation in temperature fluctuations to output faster responses to the system input [5]. The higher change in error, the higher derivative and used to anticipate future inconsistent temperatures. Equation 1 below, is the main formula used in the code to control the hardware of the project solution later in the discussion. All the PID terms are referenced as "P, I, and D" while the error between current and actual setpoint is "Error-temp".

$$\boldsymbol{PID(t) = P * Error_{Temp}(t) + I * \int Error_{Temp} + D * \frac{D(Error_{\,Temp})}{D(time)}}$$

Equation 1 [6]

1.3 PID Heater Design Requirements

The main objective is to create a PID (proportional, integral, and derivative) controlled heater system that is feasible to make, low cost and efficient for 3D filament recycler heater.

The goals of design and analysis of a "PID heat system" for a 3D Filament recycler heater are:

1. Low cost within $100 or less
2. 24V or less power system
3. Quick ramp-up temperature speed of less than 2 minutes & 30 seconds
4. Reach 210°C max for melting reusable PLA plastic (melting property)
5. Implement a PID digital control system for the heat system

For a simple heater system to work, if it reaches the temperature to melt the rated plastic and maintains the setpoint temperate consistently then the feasibility of the PID heater system is valid. The additional requirements such as cost, power, and ramp-up time is added for reducing implementation costs while optimizing the PID heater system as much as possible.

1.4 PID Heater Design Limitations

There are many types of 3D printed plastics such as ABS, PLA, ASA, and PETG. A single plastic material will be selected to simplify costs and allow more testing to produce consistent target temperature goals as there are many considerations such as viscosity, temperature range, and accessibility of plastics. A very common plastic that is widely used in 3D printers is PLA, known for its lower temperature melting range of 210°C and thus selected for this application.

This report is the design & analysis of the "PID control system" for a 3D filament recycler heater, hence the shredder or extruder systems are independent and excluded in designing the "PID heat system". A feedback sensor, heater element will be implemented and a software-to-hardware logic PID is utilized to achieve the overall implementation to prove the chosen solution.

Designing a PID loop system will depend heavily on how the microcontroller functions, typically a state machine will be implemented to feedback constant and accurate data to vary the input to for controlling the heater. Both internal & external inputs such as initial parameters to a variable physical input from a user's input will need to be added to assist controllability and tests for the heat system. Unit tests for state switching, interrupts, and function calls are potential ways of improving the overall software system design closed loop feedback. Figure 2 displays a simple PID block diagram which can be referenced for the heat system when implemented with the digital microcontroller system. The process variable can be known as the actual temperature the heater system produces and will feedback to the PID controller which will change the voltage input to the heater system based on the computed PID Controller's output that initially takes in the setpoint and process variable.

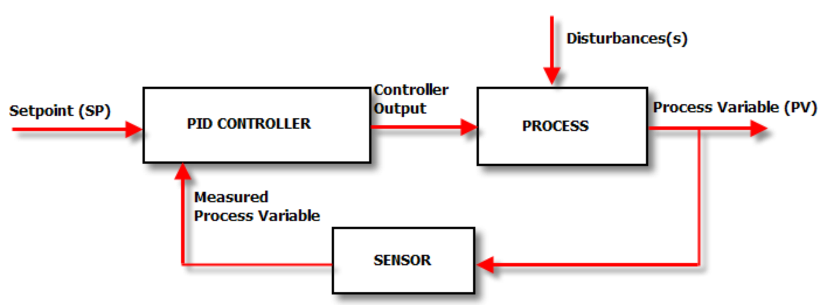

Figure 2 Generic PID closed loop block diagram [7]

1.5 Methodology

An initial assessment for a heat system would require tools such as a power source, microcontroller, sensors, and various types of heaters listed in potential solutions. A test setup such as a variable power supply can allow ramp-up temperatures tests of various voltage dependent heating systems along with a microcontroller & sensors to record temperature, time, and power characteristics quickly.

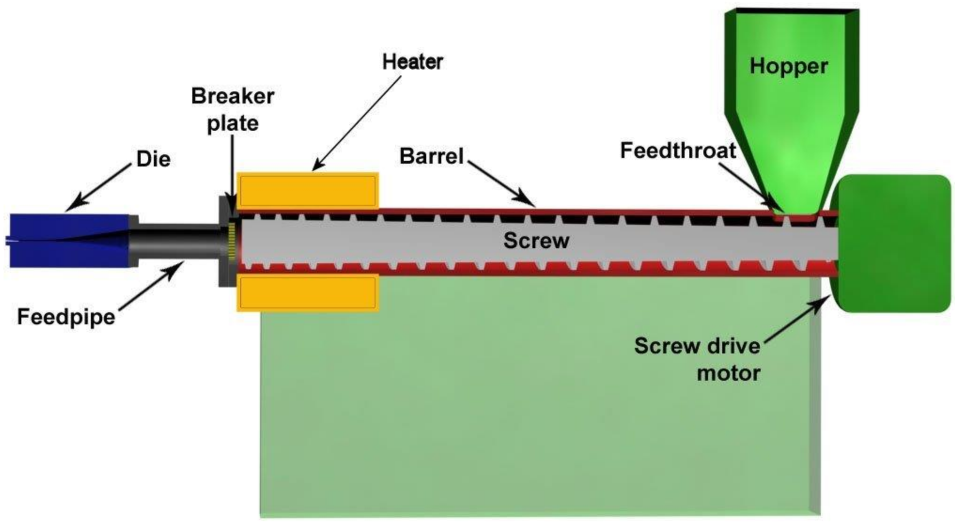

Figure 3 Ideal Final 3D Filament Recycler [8]

A broken-down cost analysis is a method in consideration for the overall design. Many components in future will have to be added to make the filament recycler. These additional components can be the motors to guide the melted plastic, sensors, buttons, LED displays, and extruder nozzle as shown for a potential product in Figure 3. Therefore, reducing the cost as much as possible specifically to the PID control heat system can help for other costs such as the heat chamber or feedpipe.

The steps above are condensed and will be used for the methodology of this project:

1. Cost Analysis & Heater System assessment
2. Chosen Heater Temperature Tests (Ramp-up times, Power usage, Efficiency & Temperature consistency)
    a. Have an insulated heat chamber/block with heat sensors around to aid setpoint temperature consistency
    b. Heat Thermistors (Sensors) to record temperature
3. MCU PID Integration (Utilize PWM, DAC/ADC sensors as necessary to implement a heat controller)
4. Test controllability and safety (Use cases and unit tests upon when initial heating of plastic begins and its duration within the heat block), Firmware State diagram

2.0 Discussion

The main part of this section includes the initial analysis on types of heater systems & current market solutions that could be a potential PID control solution based on the project requirements, design & analysis of the chosen solution, and lastly the final evaluation & feasibility of the PID control solution.

2.1 Heat System Assessment Analysis

There are various types of heaters for designing a heat system, such as an immersion, cast-in, cartridge, and coil heaters. To each heater comes benefits such as plastic melting capacity, the ramp-up temperature speed, temperature range, manufacturing costs, melting process, and heat chamber design. Most common 3D filament printers use heat resistors, nichrome wire, and heater cartridges which allows adaptability around a heat block and reaches suitable temperatures ~250℃ in which most 3D plastics melt around. Figure 4 shows nichrome wire, a heat cartridge and heat resistors usage respectively.

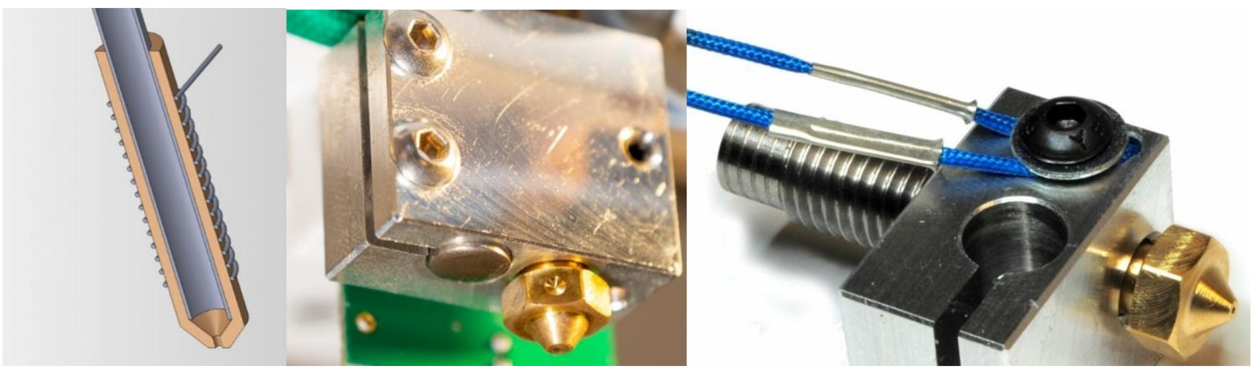

Figure 4 Nichrome (Left), Heat Cartridge (Middle), and Heat Resistors (Right) on Hot End applications [9][10][11]

2.1.1 Immersion Heater

An immersion heater would not be ideal due to the heater being "immersed" in the plastic creating direct heat to areas of the plastic which could overheat beyond its homogenous temperature property and create a solid prior to extrusion. Although it is feasible in creating heat to melt the plastic solids, it would be complex to prevent burning plastics within the process. An indirect heat is ideal to implement uniform plastic material. An example of an immersion heater would typically be used in a hot water tank or a kettle.

2.1.2 Cast-in Heater

A Cast-in heater is used in plastic processing facilities and could be a potential solution due to its design that can be adapted to various shapes and mediums to cast and mold plastic in a particular form [12]. Cast-in heaters are also durable and efficient as their typical solutions provide uniform heating based on its heat elements evenly distributed. With a uniform heating benefit comes cost due to the custom cast-in chamber but also yields potential for higher temperature ranges if needed. Figure 5 displays a cast-in heater used to process plastics. However, for a low-cost heated system this may not be the approach to account for other components for the heat system such as the PID-MCU digital control system.

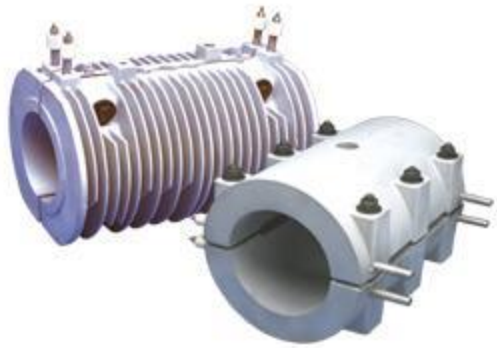

Figure 5 Cast-In Heater [13]

2.1.3 Cartridge Heater

Cartridge heaters are very commonly used with 3D printers, such as the “e3dv6” market metal hot end. The “e3dv6” uses a mini heat block that heats directly from the heater cartridge from Figure 6 and indirectly heats the nozzle to extrude plastic [13]. Instead of the use for 3D printing, this heater can also be redesigned to “heat reused plastics prior to filament extrusion”. They’re versatile due to simple heat blocks which creates an even distribution of indirect heat around the chamber, as well as low cost due to the simplicity of a heat cartridge and thermistor for accuracy and control.

Figure 6 E3DV6 Metal Hot end [14]

2.1.4 Exposed coil Heater

Exposed coil heaters have elements that “coil” around a heated chamber and in-directly heats plastics within a controlled environment. This is also another alternative solution that can be adapted to a medium as it is up to the design on what type of coils can be used and routed within the heat chamber where the plastic will change form. Coil pattern designs are shown in Figure 7 and can change based on the application. As the quality of coils can vary based on thickness and material (typically nichrome), a simple low-cost implementation of coiled nichrome around a suitable heat chamber can theoretically be possible. However, this type of heater is not typically used within 3D printing.

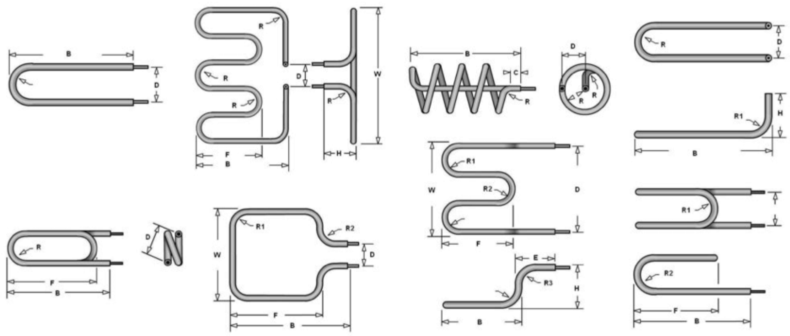

Figure 7 Types of heat-coil patterns [15]

2.2 Heater Type Decision Matrix

Table 1 Subjective Decision Matrix

Type of Heater	Cost (Avg USD $)	Volume/Medium Size (Small, medium, large plastic processes)	Manufacturing Process Complexity/ Ease of Sourcing components
Cartridge	35$ (3D Hot End Cartridges) [16]	Small Applications, enhanced with heat blocks	Easy to source online given 3D printer applications. Will need to adapt based on heat chamber, (possible heat block mount).
Coil	30$ (Nichrome Wire) [17]	Adaptable	Easy to source nichrome wire to pre-coiled wires ready to heat and test.
Cast-in	N/A, usually custom made and can be very expense due to manufacturing and common use in industries opposed to hobby, consumer level.	Adaptable	Hard to source, custom made resulting in more time to manufacture respect to project time constraints.

The cartridge heater is chosen to be the ideal candidate due to many benefits of size, implementation, power cost, PID feasibility, and common usage within 3D printing itself from Table 1. Most 3D extruder printers use heat cartridges that are inside a heat block which heats the nozzle passage when there is filament fed through it. With an open market of 3D printers, the accessibility to buying heat cartridges are very easy to source for a heat application. In addition to heat cartridges, their low power specs 12V-24V can contribute to design factors such as reducing heat loss and power draw, leaving more power to be allocated to various drivers such as the thermistor module or LCD display.

Compared to the other types of heaters such as a “cast-in” heater, there will need to be more custom designs (“made-to-order”) and expensive manufacturing which may not be feasible with the current scope of cost & time. In addition, the cartridge heater typically comes in a cylindrical shape and can be fit in a heat block/chamber nicely due to its small shape. With many distributers for 3D printers, it is very cheap and accessible to buy various heat cartridges to the user’s application.

2.3 Heat Distribution Environment & Market Analysis

Since the report is more focused upon the CENG/ECE components of the heat system, the “physical & mechanics” of the heat chamber selection will be vaguely touched upon but is a factor for placement of the heat cartridges.

Aftermarket research companies such as “ReDeTec™” and “Felfil™” have promising solutions for accounting for the heat distribution by using a “Screw barrel” system [18][19]. Recycled plastics are mixed, shredded, and passed along a “Screw barrel” system, the heat cartridges placed along the barrel and near the exit nozzle allows a nice consistent environment for the PLA to melt and extrude as a reusable filament. This solution can be adapted for the heat environment since the screw barrel insulates the heat within the cylindrical volume as a metal screw is pushing the PLA pellets through. For future implementation of other systems such as extruding the melted plastic, the screw barrel runs off a DC or Stepper gear system which can control the extrusion rate. Figure 8 displays an approach on how shredded recycled plastics pass through a screw barrel system in different zones throughout the barrel while retaining heat and melting consistently prior to extruding as a filament [20].

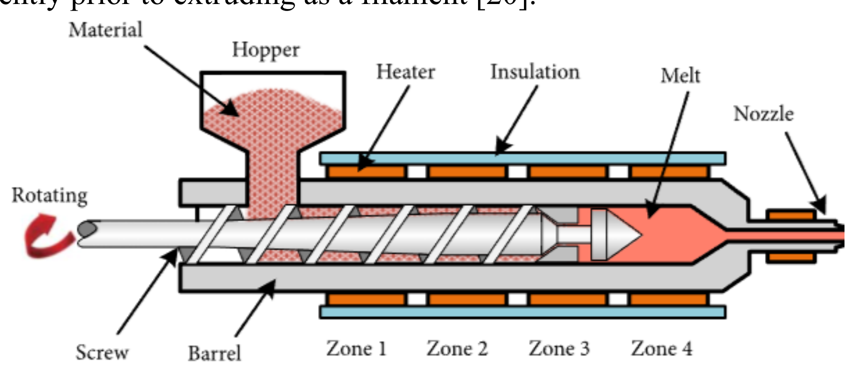

Figure 8 Screw Barrel Heat Environment [20]

For a small system application that requires less heat cartridges, room for more components (heat chamber, stepper motors, and enclosure design), the screw barrel system allows flexibility of cost and an easy way to include the nozzle diameter to the user’s ideal filament at the end of the barrel. The design of a screw barrel system can be done from reference of “ReDeTec™ PorotoCycler+” ’s screw barrel system used in their overall filament extruder shown in Figure 9 [18]. The “PorotoCycler+” however uses a band heater to account for the full diameter of the barrel which is quite unique to the design and could be an alternative approach if the chosen heat cartridges don’t produce the rated heat output in the final design. Another screw barrel heat distribution design from Felfil™ shown in Figure 10 uses three heat cartridges along a small barrel [19]. With two companies, they've proven that the screw barrel system works in melting and extruding PLA and other plastic materials such as PETG, ABS, and PVA.

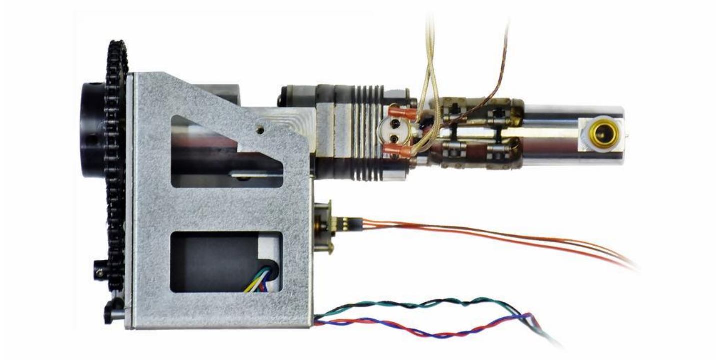

Figure 9 Screw barrel system from ReDeTec™ Filament recycler [18]

Since the accessibility of heat cartridges is cheap and easy to obtain due to popularity of 3D printer components, the reusability of 3D heat cartridges would be ideal since it's low cost and easy to implement by two input pins, voltage input and ground. Varying the voltage can be done from the PID-PWM system later shown in the PID control design section. In addition, a DC gear motor can be found with rated output torque based on the application for high-capacity plastic extrusion with an equipped screw shaft shown in Figure 11 [21]. The user would then find a screw barrel that is slightly bigger than the screw itself and place heat cartridges along the barrel from Figure 8 for heat distribution [20].

Figure 10 Felfil™ Evo Filament Extruder Components [19]

Figure 11 Screw Barrel DC Gear Motor [21]

2.4 PID Control Design – Cartridge Heater

With the assessment of various types of heaters and market solutions, this section will cover the design & analysis of the chosen cartridge heater in making the PID control system as the final heater solution. Cartridge as the heater, thermistors as the sensor, and a Mosfet-BJT circuit to control the input to the heaters are included in the circuit design for prototyping and controlled by the Arduino UNO. Note, a heat block is used instead of the screw barrel as its heating environment to focus directly upon the PID Control system feedback of its heating instead of how it extrudes.

2.4.1 PID Circuit Design

Figure 12 displays a prototype on the PID heat control system with the thermistors as the output feedback of the heat cartridge's temperature. With real time feedback, the temperature can be manually set through an encoder from the user and displayed on the LCD with its target temperature for fine-tune adjustments in melting the PLA plastic.

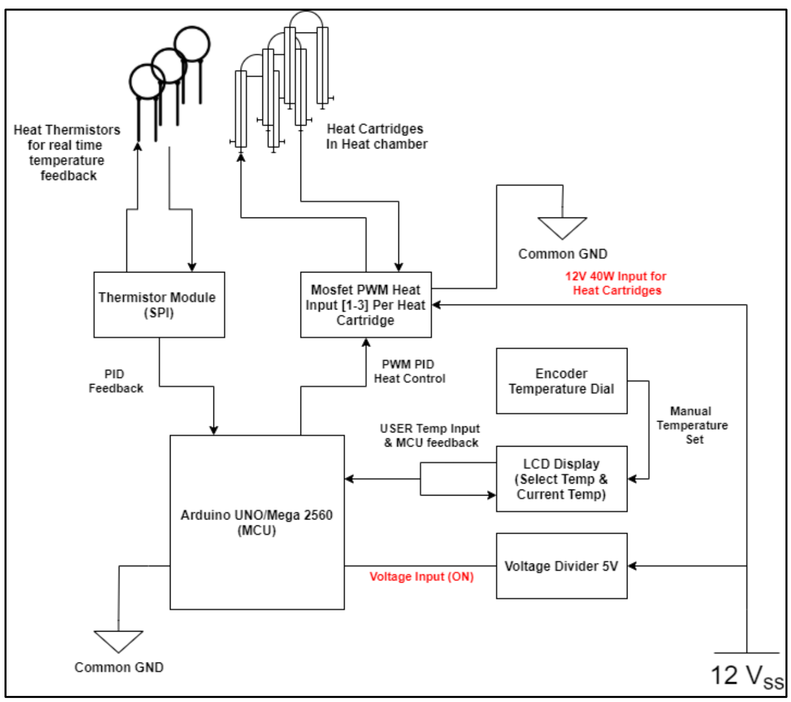

Figure 12 Electrical Circuit for PID Control Heat System

The target temperature input and feedback are all driven by the PID system coded into the Arduino, the microcontroller uses pulse width module (PWM) to vary the voltage input into the heat cartridges to ramp up to the target temperature. These PWM drivers can control each mosfet-circuit and allows fast power-switching when needed to achieve overall target temperature. Sensors used in this application are the thermistor that communicates via serial peripheral interface as well as the encoder to manually dial the target temperature. Modules used to integrate the heat system sensors are the MAX6685 Thermistor module & any 12V to 5V DC convertor.

A mosfet-GPIO integrated circuit is designed to trigger the PWM driver that controls the voltage of the heat cartridge. Figure 13 displays the mosfet circuit used to implement PWM onto the heat cartridge for the heat system. In addition, a bipolar junction transistor is used to control the higher rated mosfet from the Arduino's PWM pin. The mosfet is a voltage gate that handles 12V from the power supply and protects the Arduino from high voltage tolerance while delivering the power to the heat cartridge effectively. These components can be used to replicate this potential PID heat system solution. Lastly Figure 14 shows the physical circuit built on a prototype breadboard to further bench test and evaluate as well as Figure 15 with the LCD display with the current-target temperatures.

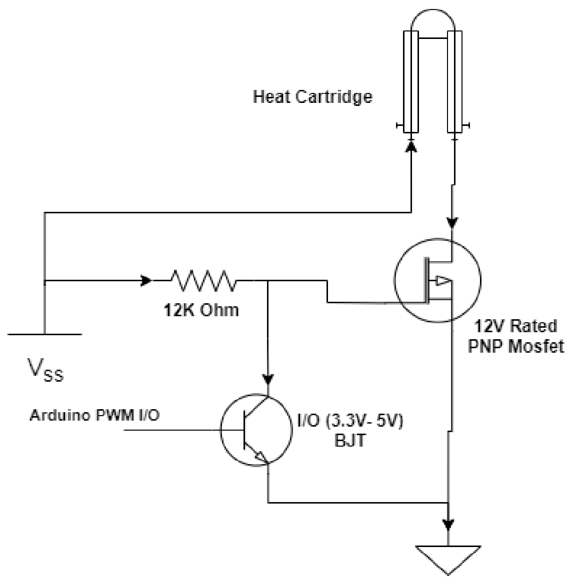

Figure 13 PWM Heat Cartridge Circuit

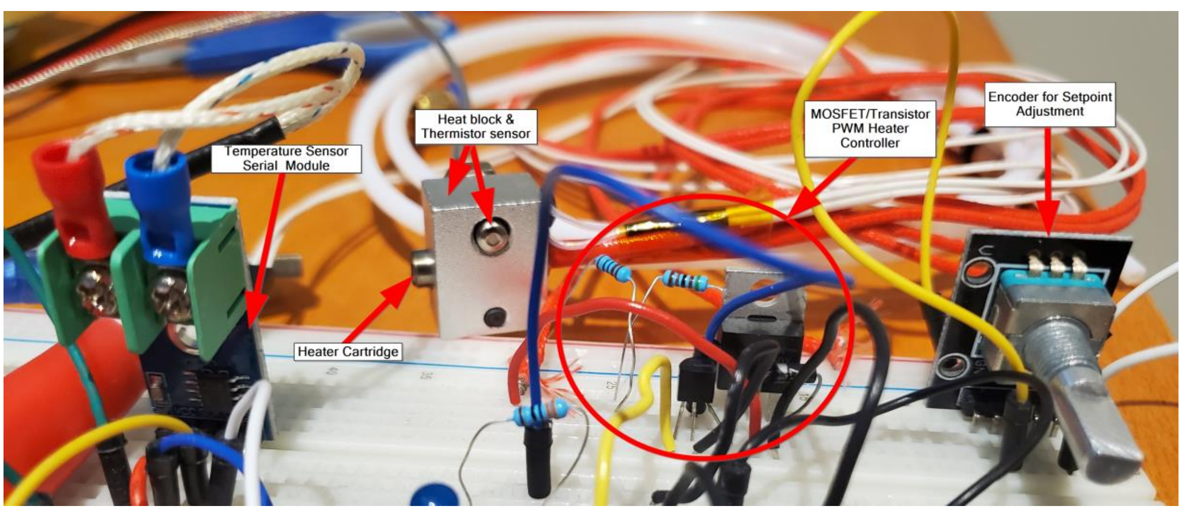

Figure 14 Physical PID Heater Cartridge Circuit

Figure 15 LCD User Display

2.4.2 PID Cost & Aligned Aims

With current components outlined in the potential solution, total voltage draw is 12V which is less than 24V in addition to the cost of roughly 64$ shown in Table 2. With the heat thermistor module rated up to 600℃ the tolerance of heat can be accounted for overshoot.

Table 2 Cost Analysis

Heat System Components	Quantity	Cost
Arduino Uno Clone	1	15$
Thermistor K-Type + Module (x2) [22]	2	32$
N-Mosfet/BJT PWM Circuit	1	10$
Heat Cartridge (12V 40W x 2) [23]	2	7$
Total cost:		64$

In theory, the 12V-40W heat cartridge is popularly used with the E3D V6 Hot end, with careful tuning the PID the temperature can go up to 400 ℃ and 300℃ effectively [24]. With all listed components and potential specs, this system is feasible within the main aims and objective of this heat system design and can melt PLA rated plastics on average of 210 ℃.

In addition to the electrical PID circuit design, the Arduino® UNO microcontroller features analog to digital pins, internal pull-up/pull-down resistors and PWM alternative functions [25]. With an open source and cloned PCB board, the Arduino can run multiple I/O ports and provide a stable 5V used for the mosfet circuit to control the voltage input for the heat cartridges. Having the pre-set functions to control these pins allows the integration of a PID system to take feedback data from the output and adjust the input of the heat system design in a feedback loop.

2.4.3 PID Control Power Budget

From Project Design Requirements, the voltage input restriction is 24V, Table 3 outlines the electrical components chosen for a possible electrical heat system design. Note, some components such as the mosfet and transistors used for the PWM circuit are rated for higher voltages but are considered as a safety factor to prevent over heating. In summary, the voltage will be supplied from a 12V power supply unit that will power the 12V heat cartridges & mosfet circuit in the PID control heater system. The Arduino Uno is powered from a USB output for controlling the LCD monitor and PWM circuit. Results of all listed components are suitable within our power budget from our voltage restriction shown in Table 3.

Table 3 Max Power Assessment

Electrical Component	Max Current Draw (A)	Max Voltage Draw (V)	Operated voltage upon use
Arduino UNO	0.04	6	USB driven, 5V
Power N-Channel Mosfet, [26]	30	60	0.00-12.00 V
BJT Transistor [27]	0.7	Vbe = 5 Vce = 20 Vcb = 30	0.00-5.00
Heat Cartridges (Qty x 2) [23]	3.3	12	0.00-12.00 V
Total Voltage (V):	5.00V-12.00V max		

2.4.4 PID Control Analysis-State Machine

The PID software control logic follows a state-machine approach, in final implementation the user will set the target temperature with initial PID gains and the PID control will update automatically based on the feedback of the heat sensor. Knowing the rate of change, and error difference respect to time, the following PID constants can be re-calculated and summed as a product for the final PID output value until the target temperature is reached using Equation 1. An analysis-state breakdown is shown on the PID state diagram in Figure 16, as described in section “1.2 Proportional Integral Derivative” the trends are implemented in respect to the PID Control heater application.

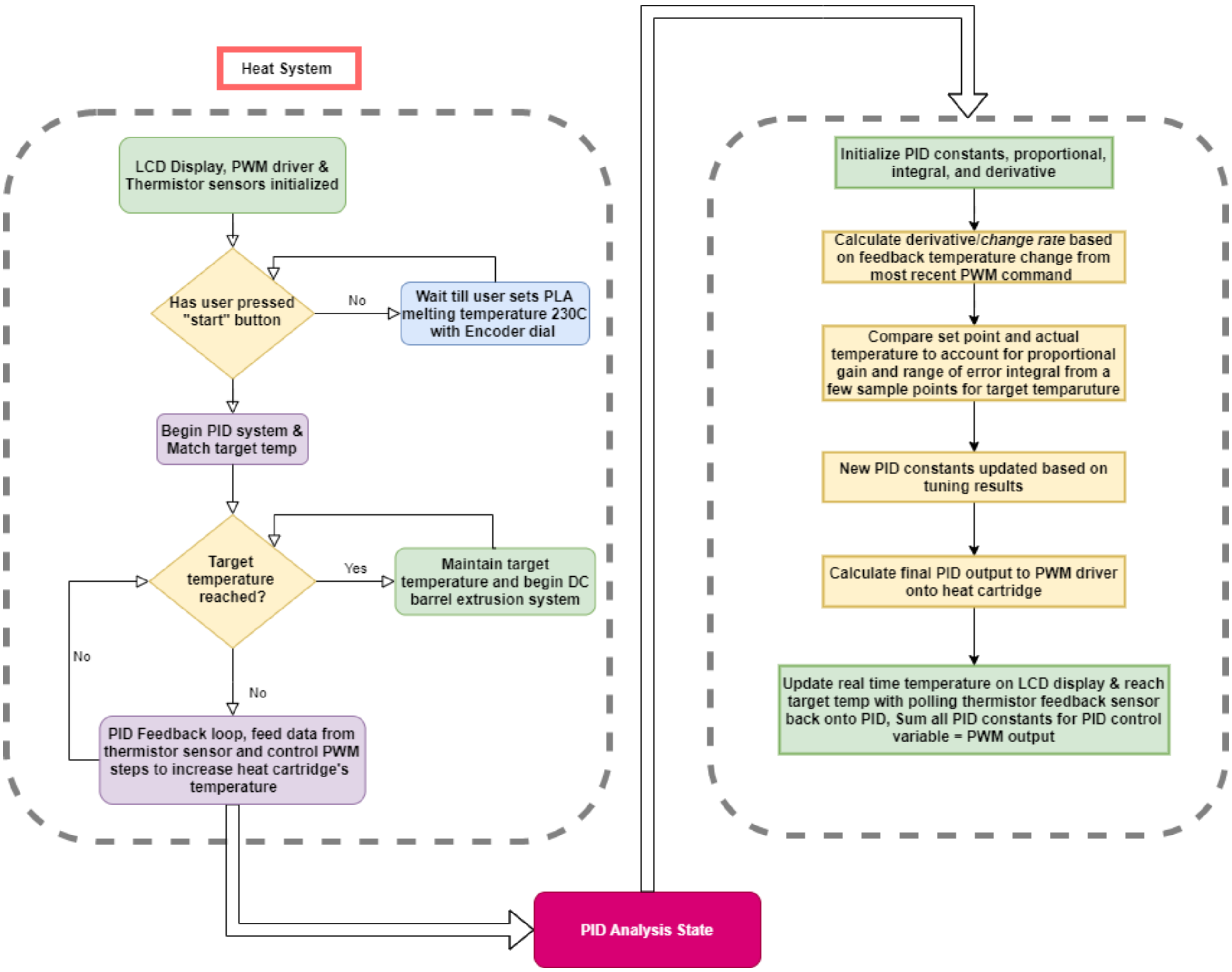

Figure 16 Heat System State machine & Analysis of the PID Heat System

2.5 PID Control Ramp-up time & Analysis

Initial testing of total ramped elapsed times up to 210 ℃ were performed on two 3D printers, the Rostock Max V2 and Ender 3 Max Pro which both also have a 12V-40W heater cartridge. They both had times of 2.30s and 2.16s average respectively [28][29]. These printers both utilize PID systems within their own custom firmware, however this gives a rough expectation given the similar 12V-40W heat cartridge ratings used in the proposed solution. With an aligned goal of less than 2:30 seconds, the PID proposed solution produced an average of 2.20s over 5 repetitive tests. The final solution result is 4.35% faster than the project requirements and reaches 210 ℃. Table 4, displays each test time and the overall average time taken to ramp-up to 210 ℃ leading to the main PLA melting temperature properties.

Table 4 Ramp-up timed Bench Test averages

3D Printer Hot Ends		1st Test	2nd Test	3rd Test	4th Test	5th Test	Average	% Difference to ramp time goal of 2:30 second
Rostock Max V2 [15]		2.34s	2.25s	2.30	2.37	2.37	2.326s	0.87% Slower than aligned ramp-up time
Creality Ender Max 3 [16]		2.10	2.07	2.11	2.17	2.13	2.116s	7.83% Faster than aligned ramp-up time
PID Control Solution		2.19	2.15	2.25	2.20	2.21	2.20s	4.35% Faster than aligned ramp-up time

Throughout the tests, a serial monitor was utilized to record timestamps and the serial output of the micro-controller. The logs were recorded and extracted for data comparisons, and a temperature ramp-up graph shown in Figure 18. Figure 17 displays an example portion of the start, end point and overshoot extracted from a test log. A basic PID functionality follows a start up to instantly ramp up to begin increasing temperature, hence the "new PID value" is "255" in stage 1 of Figure 17, this pulls the active low mosfet to "HIGH" delivering full current to the heat cartridge. After the target temperature is reached, stage 2 occurs and the PID value should start decreasing immediately, the PID value is "199" in this case. In the third stage, there is some slight overshooting, and the heater cartridge is read +2 °C higher than its target temperature. The PID system will recalculate, and as shown in stage 3 of Figure 17, the PID value is zero to bring the heat down as soon as possible.

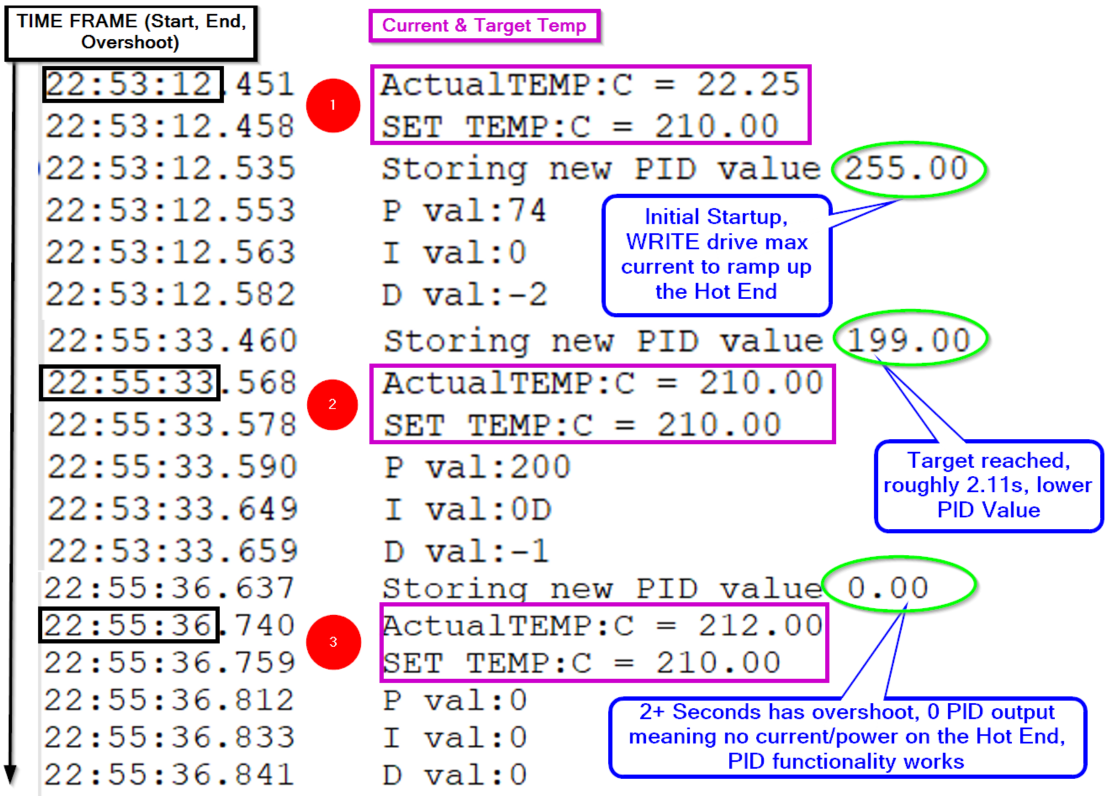

Figure 17 Start (1), End (2), and Overshoot (3) test log extraction of PID solution

With sample points logged, the extraction of temperature and time can be better shown on a ramp-up temperature graph, Figure 18, to convey the PID control solution's performance. Colour coded respectfully, the PID solution has a slightly steeper ramp up relation based off a linear approximation from start to end points. The slope value is higher than both comparable 3D printer PID hot ends and results in better heat performance within under 2:30 seconds against the ROSTOCK Hot End. There are also some fluctuations of the actual data points, high and lower points that trend linearly. Some temperature fluctuation factors could be poorly tuned P-I-D constants and the serial reader of the temperature sensor requiring a delay of 500ms to process. This produces un-ideal real time data since a desired PID control system should have feedback data as fast as possible prior to changing its final PID value onto the main process.

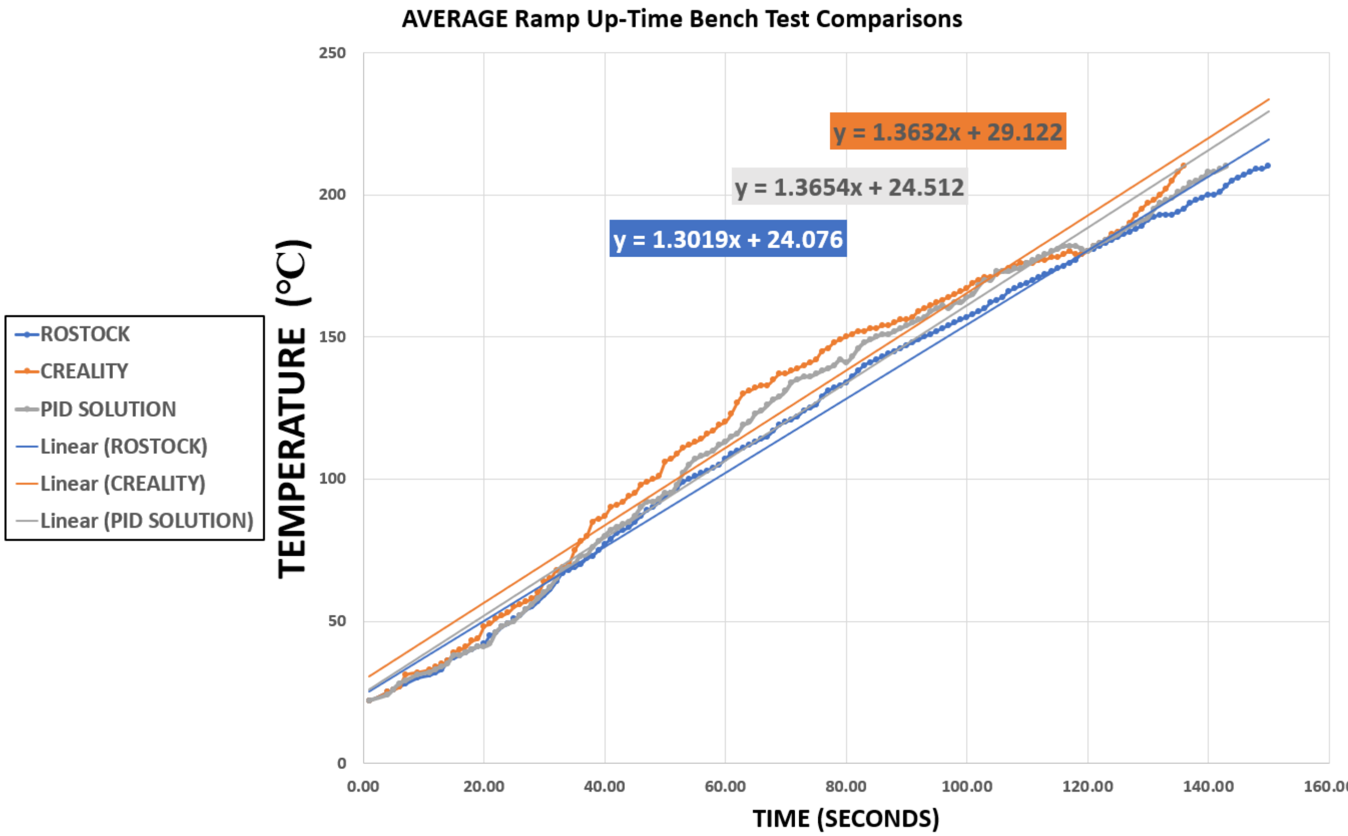

Figure 18 Ramp-up Temperature trendlines within 2:30 Minute marker

Along with having an ideal PID system, achieving steady state will prevent reused PLA plastic to become beyond melted (overshooting) than its rated target temperature as well as less heated (undershooting) prior to future implementation of flow consistent extrusion. To validate steady state, Figure 19 shows an extended duration of the PID Control solution achieving the target temperature with slight oscillations within 2-4 ℃. This oscillation is expected, factors such as the thermistor module having a +/- tolerance of 2 ℃ and possibly higher proportional coefficients results in high-to-low temperature spikes. Figure 20 displays in an ideal setting with perfect PID gains that the ramp up slope is perfectly linear and approaches a flat line representing the steady state. Although the PID solution may not fully match a perfect ideal steady state, the oscillation is sufficient within +/- 2-4 ℃.

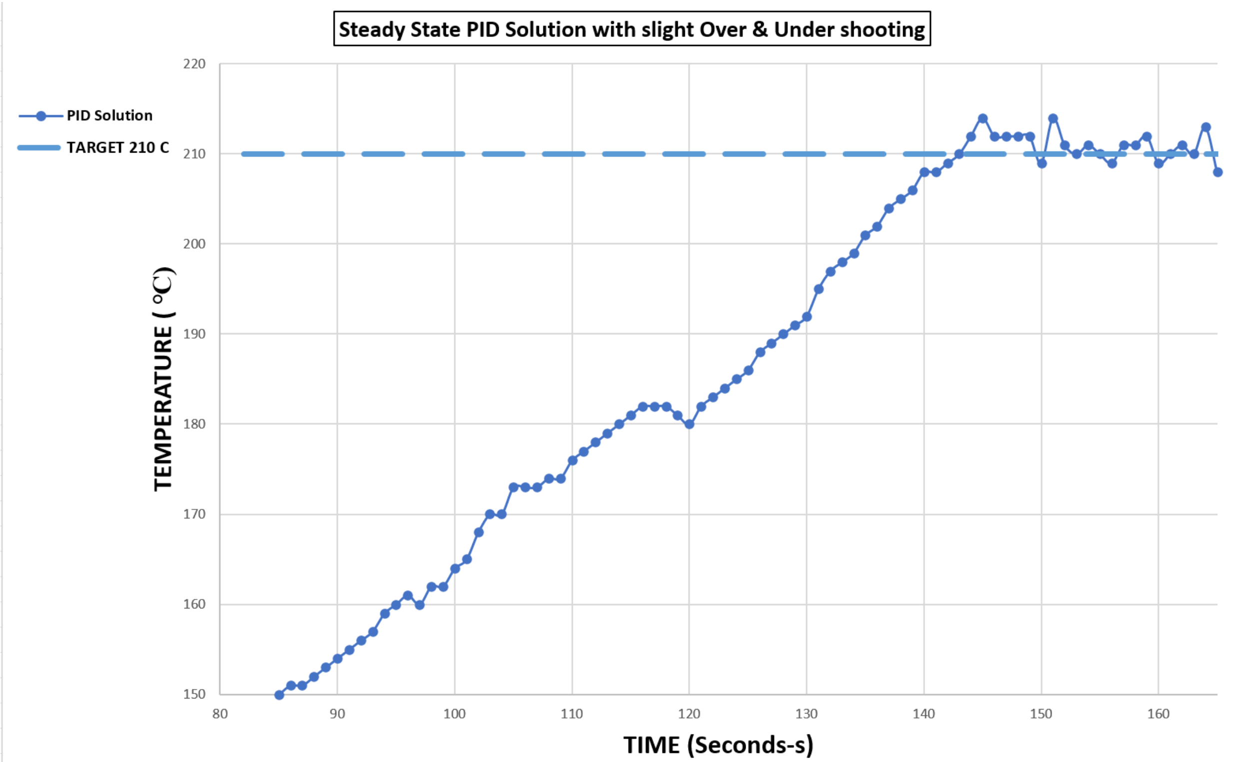

Figure 19 Steady State PID Solution with slight Over & Under – shooting

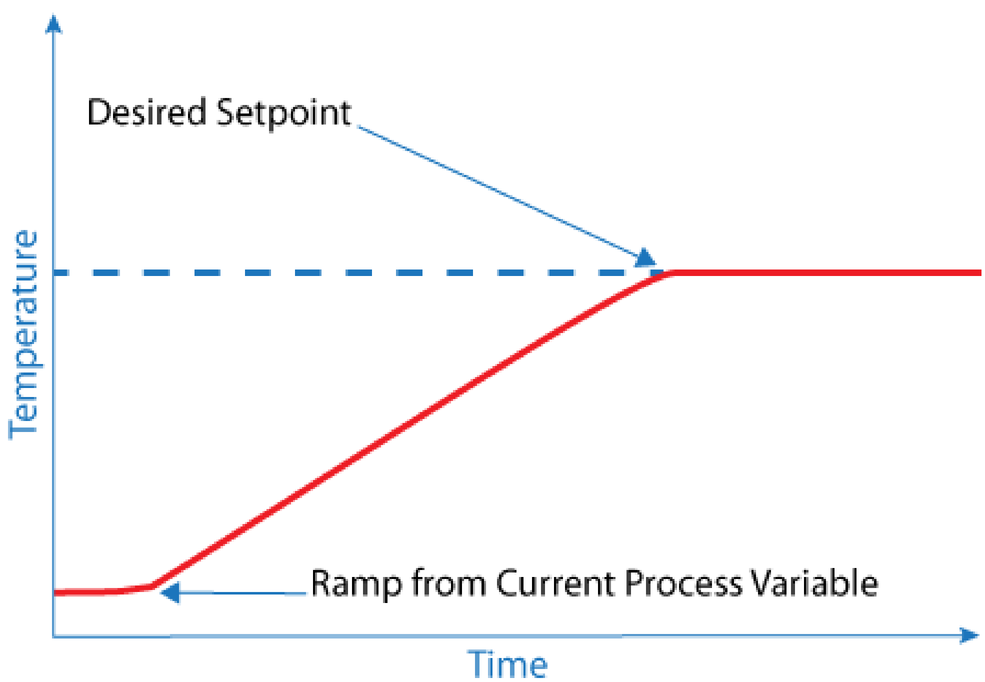

Figure 20 Perfect & Ideal linear Ramp-up to Steady State [30]

3. Conclusion

For designing a PID control for a 3D filament recycler heater, cartridge, cast-in, immersion, coil heater types were assessed based on feasibility of cost, accessibility, and implementation for melting re-used PLA plastics. Due to accessibility and common use of cartridge heaters in 3D printer applications, the cartridge heater was chosen with a low cost and provides 12 V heaters that both fit below project costs and voltage draw.

Further analysis concludes a circuit prototype controlled by an Arduino Uno to integrate the PID control logic, a power budget, a heat distribution environment assessment, and a state-flow diagram of the PID digital system implementation. The ideal heat environment was deemed to be a screw barrel system as its function allows the heat cartridges to be placed around the barrel and shredded plastics are pushed through the volume while being heated. The max voltage draw of the cartridge heater was 12.0V and is under 24V within the project requirements with higher rated mosfet, BJTs, and diodes for safety. The working circuit also shows all physical components used to perform a ramp-up test for comparison of similar hot-end specifications producing valid temperature data.

With PID Control logic used in the Arduino, a state-flow analysis was conducted to produce a closed loop system and is proven to reach steady-state at 210 ℃ with slight oscillations of around +/- 2 to 4 ℃. The closed loop PID system also includes ramp-up bench tests with the PID solution compared with two similar market hot-end PID systems used within 3D printers. The PID solution was able to ramp-up 4.35% faster to 210 ℃ than the time limit of 2 minutes and 30 seconds and a slightly steeper ramp-up slope than both ROSTOCK & CREALITY PID hot-ends. The PID Control solution met all the project requirements and reached a steady state of the rated melted PLA temperature making this project design and analysis solution successful.

4. Recommendations

3D printer technology is always improving, with better heat conduction and PID Hot end optimization. This design and analysis only covers an overall prototype integration with “restricted” power, cost parameters and “limits” high quality heaters that could be too expensive. If the user desired a faster ramp-up time, a solution could be having a higher voltage cartridge heater or higher graded cartridge heater. In addition, the PID solution produced slight oscillations so more careful tuning could be implemented and varied to prevent overshooting and undershooting. A factor to the temperature fluctuations could be the delay in which the MAX6675K thermistor module needs prior to sending the current reading of the temperature. The temperature module needs roughly a 500ms delay and gives the PID system delayed real-time feedback. A faster response thermistor module should be used to give the desired function output in future implementation. Lastly, from market research, band heaters could be an alternative solution in delivering uniform temperature across a screw-barrel system.

5. References

[1] "How To Recycle 3D Printing Filament," *3DBeginners*. [Online]. Available: https://www.3dbeginners.com/how-to-recycle-3d-printing-filament/. [Accessed: 10-Oct-2021].

[2] "PID Theory Explained," *National Instruments*. [Online]. Available: https://www.ni.com/en-ca/innovations/white-papers/06/pid-theory-explained.html . [Accessed: 3-Nov-2021].

[3] Zeki Berk, "Chapter 5 - Elements of Process Control," *Food Process Engineering and Technology*, [Online]. https://doi.org/10.1016/B978-0-12-373660-4.00005-3 . [Accessed: 3-Nov-2021].

[4] W. Bolton, "5 - Process controllers," *Instrumentation and Control System*, [Online]. https://doi.org/10.1016/B978-0-12-373660-4.00005-3 . [Accessed: 3-Nov-2021].

[5] "Understanding PID Temperature Control as Applied to Vacuum Furnace Performance," *SOLAR ATMOSPHERES*. [Online]. Available: https://solarmfg.com/wp-content/uploads/2011/01/Understanding-PID-4.pdf . [Accessed: 3-Nov-2021].

[6] "Introduction: PID Controller Design," *CONTROL TUTORIALS FOR MATLAB & SIMULINK*. [Online]. Available: https://ctms.engin.umich.edu/CTMS/index.php?example=Introduction&section=ControlPID . [Accessed: 27-Nov-2021].

[7] "PID for Dummies," *Control Solutions, Inc*. [Online]. Available: https://openmv.io/collections/cams/products/openmv-cam-h7-plus [Accessed: 10-Oct-2021].

[8] "The Filabot recycles scrap plastic into inexpensive 3D printing filaments," *NEW ATLAS*. [Online]. https://newatlas.com/filabot-plastic-recycling/25848/ [Accessed: 10-Oct-2021].

[9] "Nichrome Wire Temperature Sensing," *RepRap*. [Online]. Available: https://reprap.org/forum/read.php?1,770683. [Accessed: 10-Oct-2021].

[10] "Hot End Heater Cartridges: Everything You Need to Know," *Cleavercreations*. [Online]. Hot End Heater Cartridges: Everything You Need to Know [Accessed: 10-Oct-2021].

[11] "3D Printer Thermistor: All You Need to Know," *ALL3DP*. [Online]. Available: https://all3dp.com/2/3d-printer-thermistor/. [Accessed: 10-Oct-2021].

[12] "ELECTRIC HEATERS FOR PLASTICS PROCESSING," *WATTCO*. [Online]. Available: https://www.wattco.com/2021/07/electric-heaters-plastics-processing/ [Accessed: 10-Oct-2021].

[13] "ELECTRIC CAST-IN HEATERS," *DUREX INDUSTRIES*. [Online]. Available: https://www.durexindustries.com/electric-heaters/cast-in-heaters#case_studies-categories-60/ [Accessed: 10-Oct-2021].

[14] "Heating Coil," *E3D*. [Online]. Available: https://e3d-online.com/products/v6-all-metal-hotend [Accessed: 10-Oct-2021].

[15] "ELECTRIC HEATING COILS: SELECTION & DESIGN," *WATTCO*. [Online]. Available: https://www.wattco.com/2018/07/electric-heating-coils-selection-design/#:~:text=There%20are%20two%20main%20types,t%20suitable%20for%20all%20applications [Accessed: 10-Oct-2021].

[16] "Cartridge Heaters," *OMEGA*. [Online]. Available: https://www.omega.ca/en/industrial-heaters/c/cartridge-heaters [Accessed: 10-Oct-2021].

[17] "Heating Coil," *Amazon*. [Online]. Available: https://www.amazon.com/heating-coil/s?k=heating+coil [Accessed: 10-Oct-2021].

[18] "Meet ProtoCycler+," *ReDeTec*. [Online]. Available: https://redetec.com/ . [Accessed: 3-Nov-2021].

[19] "Felfil Evo Filament Extruder," *Felfil*. [Online]. Available: https://felfil.com/felfilevo-filament-extruder/?v=5ea34fa833a1 . [Accessed: 3-Nov-2021].

[20] Yufei Ruan, Huang Gao, Dequn Li, "Improving the Consistency of Injection Molding Products by Intelligent Temperature Compensation Control", *Advances in Polymer Technology*, [Online]. https://doi.org/10.1155/2019/1591204 . [Accessed: 3-Nov-2021].

[21] "DC 6V 12V Gear Motor 1024GA20 Thread Flip N20 Gear Motor M4 x 55mm Shaft(6V 60RPM)," *DREAMS*. [Online]. Available: https://www.dreamskyt.com/index.php?main_page=product_info&products_id=39900 . [Accessed: 3-Nov-2021].

[22] "MAX6675 K-TYPE THERMOCOUPLE MODULE AND SENSOR," *PHIPPS ELECTRONICS*. [Online]. Available: https://www.phippselectronics.com/product/max6675-k-type-thermocouple-module-sensor/ . [Accessed: 3-Nov-2021].

[23] "Ewigkeit 12V 40W 620 Ceramic Cartridge Heater and NTC Thermistor 100K 3950 for 3D Printer(Pack of 10pcs)," *Amazon*. [Online]. Available: https://www.amazon.ca/gp/product/B073TVBJVY/ref=ox_sc_act_title_2?smid=ABJP334RWT1YX&psc=1 . [Accessed: 3-Nov-2021].

[24] "E3D V6 All-Metal HotEnd," *DAEMON 3D PRINT*. [Online]. Available: https://www.daemon3dprint.com/main/e3d-v6-all-metal-hotend.html . [Accessed: 3-Nov-2021].

[25] "CANADUINO® 3 x ATmega328P Module Compatible with Arduino UNO R3 - CH340 USB," *Amazon*. [Online]. Available: https://www.amazon.ca/CANADUINO-ATmega328P-Module-Compatible-Arduino/dp/B07ZQQLDD9/ref=sr_1_33?keywords=arduino+clone&qid=1636234697&sr=8-33 . [Accessed: 3-Nov-2021].

[26] "N-Channel MOSFET 60V 30A," *Sparkfun*. [Online]. Available: https://www.sparkfun.com/products/10213 . [Accessed: 3-Nov-2021].

[27] "S8050 - NPN Transistor," *COMPONENTS101*. [Online]. Available: https://components101.com/transistors/s8050-transistor-pinout-equivalent-datasheet . [Accessed: 3-Nov-2021].

[28] "ROSTOCK MAX™ V2 DESKTOP 3D PRINTER KIT," *SeeMeCNC*. [Online]. Available: https://www.seemecnc.com/products/rostock-max-complete-kit . [Accessed: 3-Nov-2021].

[29] "Ender-3 Max 3D Printer," *Creality*. [Online]. Available: https://www.creality3dofficial.com/products/ender-3-max-3d-printer . [Accessed: 3-Nov-2021].

[30] "Understanding Setpoint Ramping and Ramp/Soak Temperature Control," *WEST Control Solutions*. [Online]. Available: https://www.west-cs.com/news/understanding-setpoint-ramping-and-rampsoak-temperature-control/ . [Accessed: 27-Nov-2021].

6. Appendix

6.1 PID CODE

```
/////////////////////////////////////////// CODE START /////////////////////////////////////////////////////////////////////

#include <LiquidCrystal_I2C.h>
#include <Wire.h>
#include <SPI.h>


#include "max6675.h"

//Pins for the SPI with MAX6675
int thermoDO = 4;
int thermoCS = 5;
int thermoCLK = 6;

//Pins for the SPI with MAX6675
#define MAX6675_CS   5
#define MAX6675_SO   4
#define MAX6675_SCK  6

MAX6675 thermocouple(thermoCLK, thermoCS, thermoDO);

LiquidCrystal_I2C lcd(0x27,20,4);  // set the LCD address to 0x27 for a 16 chars and 2 line
display

int PWM_pin = 3;  //Pin for PWM signal to the MOSFET driver (the BJT npn with pullup)

/*    i2c LCD Module  ==>   Arduino
 *    SCL             ==>     A5
 *    SDA             ==>     A4
 *    Vcc             ==>     Vcc (5v)
 *    Gnd             ==>     Gnd      */


//Variables
float set_temperature = 210;            //Default temperature setpoint. Leave it 0 and control it with
rotary encoder

float temperature_read = 0.0;
float PID_error = 0;
float previous_error = 0;
float elapsedTime, Time, timePrev,timetot;
float PID_value = 0;
```

```
int button_pressed = 0;
int menu_activated=0;
float last_set_temperature = 0;

//PID constants
//////////////////////////////////////////////////////////
int kp = 40;   int ki = 3;   int kd = 80;//80
//ROSTOCK 36 -3 - 90
//21,3,51-80
//////////////////////////////////////////////////////////

int PID_p = 0;    int PID_i = 0;    int PID_d = 0;
float last_kp = 0;
float last_ki = 0;
float last_kd = 0;

int PID_values_fixed =0;



void setup() {
  pinMode(PWM_pin,OUTPUT);
  TCCR2B = TCCR2B & B11111000 | 0x03;    // pin 3 and 11 PWM frequency of 928.5 Hz
  Time = timetot = millis();

  lcd.init();                    // initialize the lcd
  lcd.backlight();
  Serial.begin(9600);

  Serial.println("MAX6675 test");
  // wait for MAX chip to stabilize
  //delay(500);
}

void loop() {

  // First we read the real value of temperature
  Serial.print("Recent Actual TEMP:");
  temperature_read = readThermocouple();//thermocouple.readCelsius();

  Serial.println(temperature_read);
  //delay(1000);

  //Next we calculate the error between the setpoint and the real value
  PID_error = set_temperature - temperature_read + 5;
  //Calculate the P value
```

```
  PID_p = kp * PID_error;
  //Calculate the I value in a range on +-3

  if(PID_error > -3 && PID_error < 3)
  {
    PID_i = PID_i + (ki * PID_error);
  }


   //For derivative we need real time to calculate speed change rate
  timePrev = Time;                          // the previous time is stored before the actual time read
  Time = millis();                          // actual time read
  elapsedTime = (Time - timePrev) / 1000;
  //Now we can calculate the D calue
  PID_d = 0.01*kd*((PID_error - previous_error)/elapsedTime);
  //Final total PID value is the sum of P + I + D
  PID_value = PID_p + PID_i + PID_d;

  //We define PWM range between 0 and 255
  if(PID_value < 0)
  {    PID_value = 0;    }
  if(PID_value > 255)
  {    PID_value = 255;  }
  Serial.print("Storing new PID value");
  Serial.println(PID_value);
  Serial.println("P val:" +  (String)PID_p);
  Serial.println("I val:" +  (String)PID_i);
  Serial.println("D val:" +  (String)PID_d);

  //Now we can write the PWM signal to the mosfet on digital pin D3
  //Since we activate the MOSFET with a 0 to the base of the BJT, we write 255-PID value
(inverted)
  analogWrite(PWM_pin,255-PID_value);
  previous_error = PID_error;     //Remember to store the previous error for next loop.

  delay(100); //Refresh rate + delay of LCD print
//   lcd.clear();
   Serial.print("ActualTEMP:");
   Serial.print("C = ");
   Serial.println(temperature_read);
   Serial.print("SET TEMP:");
   Serial.print("C = ");
   Serial.println(set_temperature);
   lcd.clear();
   lcd.print("REAL TEMP:");
   lcd.print(temperature_read);
```

```
  lcd.print("C");
  lcd.setCursor(0, 1);
  lcd.print("SET TEMP:");
  lcd.print(set_temperature);
  lcd.print("C");
  if( temperature_read >= set_temperature){
   Serial.print("Time taken total:" );
   Serial.print(timetot);
   Serial.println("ms");
   Serial.println("P val:" +  (String)PID_p);
   Serial.println("I val:" +  (String)PID_i);
   Serial.println("D val:" +  (String)PID_d);
   Serial.print("Actual TEMP:");
   Serial.print("C = ");
   Serial.println(temperature_read);
   //delay(1000);
   Serial.print("SET TEMP:");
   Serial.print("C = ");
   Serial.println(set_temperature);
  }
 // delay(250); //Refresh rate + delay of LCD print

//   lcd.print("C = ");
//   lcd.print(thermocouple.readCelsius());


//
//  //////////////////////////////////////////////////////////////////////////////////OLD
//  // basic readout test, just print the current temp
//   lcd.clear();
//   Serial.print("C = ");
//   Serial.println(thermocouple.readCelsius());
//   lcd.print("C = ");
//   lcd.print(thermocouple.readCelsius());
//   Serial.print("F = ");
//   Serial.println(thermocouple.readFahrenheit());
//
//   // For the MAX6675 to update, you must delay AT LEAST 250ms between reads!
//   delay(1000);
}



//The function that reads the SPI data from MAX6675
double readThermocouple() {
```

```
  uint16_t v;
  pinMode(MAX6675_CS, OUTPUT);
  pinMode(MAX6675_SO, INPUT);
  pinMode(MAX6675_SCK, OUTPUT);

  digitalWrite(MAX6675_CS, LOW);
  delay(1);

  // Read in 16 bits,
  //  15    = 0 always
  //  14..2 = 0.25 degree counts MSB First
  //  2     = 1 if thermocouple is open circuit
  //  1..0  = uninteresting status

  v = shiftIn(MAX6675_SO, MAX6675_SCK, MSBFIRST);
  v <<= 8;
  v |= shiftIn(MAX6675_SO, MAX6675_SCK, MSBFIRST);

  digitalWrite(MAX6675_CS, HIGH);
  if (v & 0x4)
  {
    // Bit 2 indicates if the thermocouple is disconnected
    return NAN;
  }

  // The lower three bits (0,1,2) are discarded status bits
  v >>= 3;

  // The remaining bits are the number of 0.25 degree (C) counts
  return v*0.25;
}



///////////////////////////////////////////////// CODE END ///////////////////////////////////////////////////////////////////////////
```