Makerspace: Recycling Printed PLA into Spooled PLA

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Abstract

3D printing has become a large industry in the world, with the technology being used in many different fields. However, the use of 3D printing has led to an influx of plastic waste, most notably PLA plastics. This PLA waste can range to support material used during the printing process, failed prints, and completed prints that have served their purpose. This can be seen at Worcester Polytechnic Institute's Makerspace located at Innovation Studio, having a prototyping lab that runs a large amount of 3D printers for students to utilize. Due to many classes and projects having a dependence on rapid prototyping, the makerspace is constantly using PLA to print plastic parts, which in turn creates more and more PLA waste. To solve this problem, previous students attempted to build a system to recycle PLA plastic into new filament to use in the 3D printers. There were two iterations of the project, each using their own method of attempting to recycle PLA. The goal of the project is to improve upon these previous iterations and find potential flaws that are hindering the recycling process to make a more efficient recycling system. These iterations utilized a system to grind plastic parts into smaller pieces, then feed these pieces into a hot end, softening the plastic and causing it to extrude as a 1.75mm strand of filament. This would then leave the hot end to be collected in a spool, ready to be used in a 3D printer.

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Introduction

3D printing produces a large amount of plastic waste, which is becoming a large problem. These devices allow easy access to manufacturing and the freedom to test out new ideas, but it is also accompanied by an increase in errors and the accumulation of useless items. Because of this, the plastics are ending up in landfills that could easily be reused and repurposed. The precise statistics of how much waste 3D printing generates are difficult to grasp. This is especially true given that the process is increasingly being used in more hobbyists' homes every year.

During 2021 Filamentive conducted a survey on 3D printer users in the UK, and based on the more than 200 responses it received, the company forecasts that 278,400 kg of 3D printing materials will be dumped in landfills across the UK in 2021(Toor, 2021). The University of California at Berkeley noted in 2017 that their collection of 100 3D printers generated at least 600 lbs of wasted filament within that year, putting the situation into perspective (Brice, 2017). Those are significant figures that increase the already alarming daily disposal of plastics.

Thankfully, PLA, the most widely used material for 3D printing, is at least partially biodegradable. Since it is made of cornstarch, it degrades more quickly than filaments made of synthetic materials like ABS. Learning more about PLA reveals that it is a thermoplastic polyester polymer. The term "thermoplastic" refers to a particular class of plastic that, when heated to a specific temperature, softens and can be molded. Furthermore, the term "polyester" here refers to a polymer made up of chemicals found in nature, such as those found in plant cuticles (*Polylactic acid*, 2024). In essence, PLA is shaped by the waxy components of plants, which helps it decompose into biodegradable components rather than remaining whole in a landfill forever. However, these properties can be misleading to how compostable PLA actually is.

While PLA can decompose into biodegradable components, it requires specific conditions to do so. Moisture and heat over 140°F are required for PLA to start the self-hydrolyzation process, which lowers the polymer's molecular weight to lactic acid. Without these conditions, PLA cannot and will not degrade; for example, if your home compost pile does not reach 140°F and is devoid of water, PLA will not degrade. It is crucial to understand that PLA is not a material that degrades in just any environment; rather, it is only compostable in industrial settings and exhibits very little mineralization (not decomposition) in the majority of settings (Li et al., 2022).

This leads to the question of if PLA is recyclable. The short answer is yes, PLA filament can be recycled, but not in the same way that milk jugs, food containers, and other common plastics can. PLA cannot be bundled with the other plastics because it has a lower melting point than the others. There are two main ways to recycle PLA filament at the moment, which are to either give the PLA waste to a recycling plant that has the capability of recycling it, or by grinding it up and extruding it into new filament. The goal of this project is to attempt the second method of recycling PLA filament.

Background

In order to properly recycle PLA plastics, they need to be processed in a way that allows it to be reused in a 3D printer. This requires shredding the plastics into smaller, consistent pieces, cleaning the plastics of any dirt and debris, heating up the plastics to a specific temperature, extruding the plastic to form PLA filament, and spooling the filament to be ready to use again.

Shredding is arguably the most important part of the process, as it transforms the PLA plastic into a more processable form. Many plastic manufacturers create plastics in the form of small pellets, which filament companies then buy to turn into their own filaments. The goal of shredding plastics is to get it back into the small pellet form, which then allows the plastics to be easily processed into a new form. Many companies will buy clear plastic pellets as it allows them to modify certain aspects of the plastic such as color, however, this is not a concern with the project.

Cleaning the plastics is another important aspect, as it ensures there aren't any contaminants that could cause possible problems with using the filament. This step requires not only cleaning but also drying out the filament, as PLA is known for being hygroscopic meaning that it absorbs moisture from the air. Without drying the PLA the absorbed moisture evaporates and can result in bubbling and imperfections in the extruded filament. Therefore, it is important to not only clean the plastics but also remove any moisture from them to ensure the quality of the PLA.

There is also the shaping of the plastic into a filament, which requires heating and extruding the PLA plastic. These pellets will be fed into a filament extruder that will melt the pellets, allowing them to be malleable and shaped easily into any form. The pellets then bond together and take on the characteristics of a consistent, stranded material. Through a circular nozzle, the string-like bonded material, also known as filament, exits the heating chamber and continues to the cooling section. This cooling section uses a moving liquid or gas such as water or air to help bring the temperature down and allow it to form a consistent cylindrical shape. Many 3D printers rely on the filament being perfectly cylindrical with its diameter length being 1.75mm, which is another major challenge of this project. The speed at which the filament is pulled through the cooling chamber defines the diameter of the filament, with slower pulling leading to a larger diameter and faster pulling leading to a smaller diameter.

Finally, there is the process of spooling the filament. There are usually two roles of the spooler, which is checking the diameter of the filament and controlling the speed at which the filament is wound. This then leads to the final product of the PLA filament, ready to be reused in a 3D printer.

To better optimize this step of the process, a range of sensors can be used to measure filament output. Typically 3D printers, such as the Prusa, use optical filament sensors to detect the presence of material, measure and monitor their movement, and ensure that extruded, or melted filament, is the right size to be used with the printer. By adjusting pull speed and melting temperature proportionally to what is received from our sensors we can ensure that the formed filament is the correct size and shape. Another sensor that may be employed would be for both temperature and humidity during the melting process. In order to properly melt our PLA into a recyclable consistency we have to ensure that the heat chamber distributes heat evenly to all materials occupying its area.

Thermal Properties

The thermal properties of the polylactic acid are the most important property to be taken into consideration when recycling. Below in Table 1 the thermal properties of polylactic acid are detailed. Understanding the thermal properties of PLA is essential in determining the optimal melting temperature due to changes in viscosity and shear rate at given temperature within the given ranges. The changes in viscosity have a major impact upon the overall flow rate, between the screw speed and discharge rate of material there needs to be a balance between an optimal production speed and over extrusion of material.

Table 1 : PLA Properties (ScienceDirect)

Property	PLA
3D Printing Temperatures	200 to 220°C
Melting Temperatures	130 to 180°C
Glass Transition Temperature	55 to 60°C (amorphous) 60 to 80°C (semi-crystalline)
Crystallization Temperature	90-110°C 25%-30% crystallinity
Density	1.210 to 1.430 g/cm^3
Modulus of Elasticity	2.7 to 16 Gpa
Yield Strength	50-55 MPa

As seen in Table 1 the material we'll be melting melts between 130°C and 180°C which is the target range for the extruder operating temperature. Using either a well-placed temperature sensor, near the center of the chamber, or a range of temperature sensors in the chamber, we may ensure that our PLA will melt consistently throughout. A humidity sensor would provide additional checks to make sure the PLA is able to start the self-hydrolyzation process properly.

There are several factors that contribute to measuring and adjusting PLA melting points. First, the state of our PLA must be taken into consideration. At best the pellets should be standardized in size or shape, and clear of contaminants such as dust or moisture. We may also have to make sure the 3D prints introduced into our process are composed entirely of PLA. Some printers may use PVA to support their structure so we'll have to check before melting. The rate at which we heat our material is also a factor in the process. If the PLA is melted too quickly the melting point may be raised. The cooling rate would also have to be factored as stronger bonds are formed when the print is cooled slowly.

PLA is sensitive to prolonged exposure to high temperatures, which can lead to thermal degradation. Thermal degradation of a material results in a decrease of strength and an increase in brittleness, which can cause chipping, breaking, and cracking in the material (Signori et al., 2009). During recycling, it's essential to prevent the polymer from reaching temperatures that could cause decomposition or the formation of unwanted byproducts. Unwanted byproducts raise several concerns, including clogs in the extruder, toxic fumes, and structural defects. Next, a relative humidity of 90 percent would be necessary to ensure the self-hydrolyzation process is active while reducing the amount of steam generated in the heat chamber. By creating a system that takes in temperature and humidity data and adjusts the system accordingly we may be able to create a closed-loop system. This system would potentially be able to operate and adjust its own process without human interaction having to be in the loop. The optimal goal for our project would be to simply insert 3D prints and output PLA with our recycler handling all processes in between.

To ensure proper communication between our sensors and the main recycler system we needed to utilize the Robot Operating System application. Depending on design and budget constraints some sensors may not be able to directly communicate with one another through the system's main processing device, an Arduino Mega.

Solutions in Plastic Recycling

The recycling of PLA is becoming increasingly important in the efforts to create a more sustainable and environmentally responsible approach to 3D printing and plastic production. Several companies are taking innovative steps to tackle the recycling challenges associated with PLA, and this section highlights a few of the leaders in this space setting the precedent for PLA recycling.

3devo

3devo is a Dutch company that specializes in the development of advanced filament extrusion systems, with a focus on plastic recycling and sustainable material production. The company has gained recognition for its SHR3D IT system, which is designed to shred, melt, and extrude various plastic materials, including PLA, into high-quality filament for 3D printing and other applications. In addition, they also offer a standalone desktop Filament Maker that allows users to melt down pellets to create their own custom filament (*Our Approach | 3devo*).

Filabot

Based in Vermont, USA, Filabot is a prominent company in the field of recycling PLA and other thermoplastics for 3D printing. They have developed a range of products that allow users to recycle and extrude their own 3D printer filament. The Filabot system grinds down discarded PLA parts and transforms them into pellets that can then be melted and re-extruded into a spool of filament. Filabot offers a two-stage shredding process that ensures the pellets have a uniform size gradient before they are loaded into the extruder (*EX6 Filament Extruder - Standard Series*).

ReDeTec

ReDeTec is a company that specializes in providing solutions for recycling plastic waste, particularly for 3D printing applications. The company is well-known for its product called the "ProtoCycler," which is designed to efficiently recycle various thermoplastics, including PLA, and turn them into high-quality 3D printing filament. ReDeTec's flagship product, the ProtoCycler, is a filament extrusion system that enables users to recycle plastic waste and convert it into 3D printing filament. The ProtoCycler system consists of an integrated grinder, extruder, and spooler, making it a compact and convenient solution. ReDeTec maintains an open-source approach, sharing design files and encouraging collaboration within the 3D printing community. This promotes innovation and knowledge sharing and has pushed them to the forefront of plastics recycling (*MixFlow*).

Design Process and Fabrication

The design process involved breaking down the system into four subassemblies: Heating, Cooling, Measurement, and Controls. Many aspects of this system drew inspiration from past iterations of this project, along with open-source projects available online. During weekly meetings, we explored different design iterations and conducted testing to determine the optimal design.

Heating

To set the heat chamber to the desired temperature the encasing metal was fixed with two cartridge heaters supplied with 24 volts and two thermistor sensors. Using a standard thermistor circuit[1]* we can measure the internal temperature of the heat chamber. The voltage is measured using the following formula $V_o = R_1/(R_1 + R_2) * V_{cc}$. Vcc is the voltage source supplying power to the circuit, R1 is the variable resistance of the thermistor, and R2 is a fixed resistance used as a base to measure the total resistance within the circuit. Then by reading the variance in resistance as the thermistor heats up, we can convert an analog reading to the temperature read from the thermistor. The heater is supplied with 24 volts using a 5V one-channel relay module* and remains on until the desired temperature is read by the average value of the two thermistors.

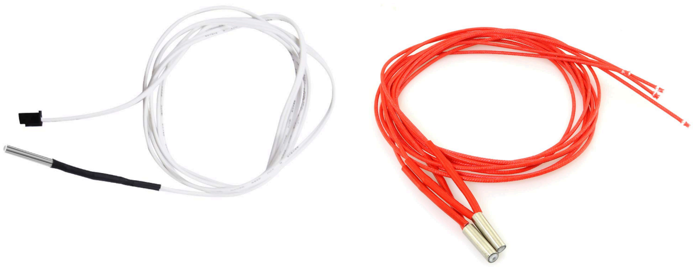


Figure 1: Left - Thermistor, Right - Cartridge Heater

For the heating controller, an Arduino Uno controlled it by heating the extruder nozzle with the heaters until a measured peak temperature of 139°C was reached as measured by the thermistors. Then the controller worked to keep the temperature at around the set peak in order to melt the PLA but not melt it too much.If the plastic became too hot, it would start to melt out of the extruder too fast to keep a consistent shape and size of the recycled PLA material. It would begin to become too soft to wind onto the spool properly due to it stretching out of shape and detaching too easily. This would cause issues in future reuse of the recycled PLA since it would be misshapen and potentially also be too thin than anticipated.

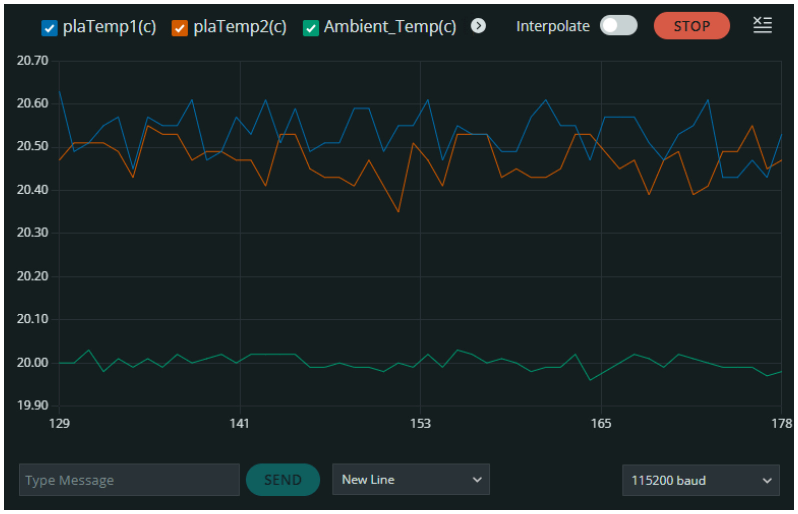


Figure 2: Temperature readings of the PLA.

Extrusion

To extrude the PLA into filament the heat chamber, made out of stainless steel, also contains an auger that is used to force the melted PLA out of the output nozzle. The auger is powered by a Nema 23 stepper motor which rotates to extrude PLA and its speed can be controlled by our Arduino mega.

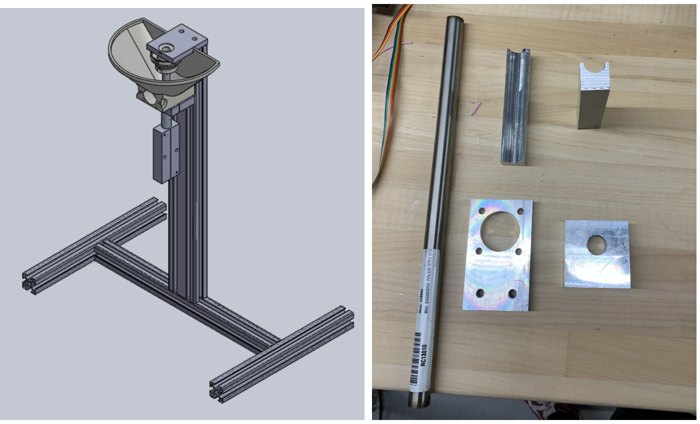


Figure 3: Left - The CAD diagram of the extruder, Right - Parts used during its construction.

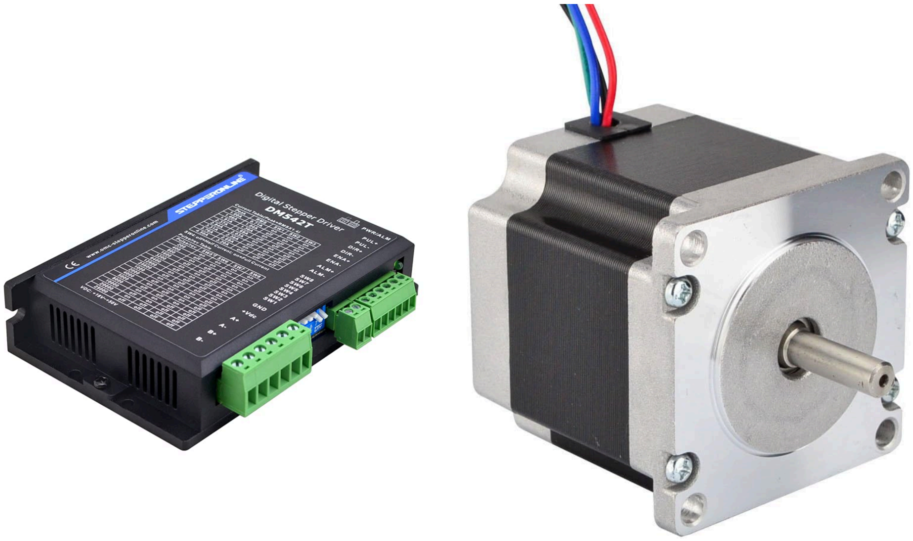


Figure 4: On the left is the stepper controller and on the right is the Nema 23 stepper motor used in the extruder.

The controller for the extruder motor was fairly simple. The temperature of the heaters was sent to the Arduino Mega controller that included the extruder motor and, once it got hot enough, it turned the extruder motor on. The specific temperature set was 137°C which is shortly after the melting temperature of PLA at 130°C. After 137°C, the extruder motor simply turned on to a speed that we found to be satisfactory after much testing.

Cooling

For the cooling of the extruded PLA, a dynamic cooling system was implemented on an Arduino Mega. The PLA needed to be cooled in order to be wrapped around the spool but it needed to be kept from becoming too cool, otherwise the PLA would not wind well around the spool. It could snap or simply just wind into an undesirable shape or form which would cause problems for future use of recycled PLA. To achieve this, two PWM fans of controllable speed with a maximum cubic feet per minute output of 4.27 were used. These fans were chosen due to their PWM input pin which could control the speed easily within the controller. In addition, the maximum airflow output was more than enough for what the estimated range would need to be. The fans also had ducts attached to them which were done so in order to focus the airflow more on to the extruded PLA. The specific ducts used stated they would not have any constriction on the fans which was particularly useful here since the controller's cooling equations would have then needed to take into account any constriction of the fans' output airflow if there had been any. The cooling equations used were the following set of equations: $Q = \frac{P}{\Delta T}$, where Q is the required airflow in cubic feet per minute, P is the heat dissipation rate in Watts, and ΔT is the temperature difference between the ambient air and the desired operating temperature in °C (How do I calculate the required airflow for a cooling fan?). Then $P = \frac{T_{PLA} - T_A}{R}$, where T_{PLA} is the temperature of the PLA in $°C$, T_A is the temperature of the ambient air in $°C$, and R is the thermal resistance of the component in $\frac{°C}{Watts}$ (How to Calculate Heat Dissipation to Prevent Overheating). Finally, $R = \frac{L}{kA}$, where L is the thickness of the material in meters, A is the cross-sectional area perpendicular to the heat flow in meters squared, and k is the material’s thermal conductivity in $\frac{Watts}{Meters \bullet °C}$ (Thermal Resistance – Thermal Resistivity). The ambient air and temperature of the PLA were measured using two Gravity: I2C Non-contact IR Temperature

Sensors (MLX90614-DCI) from DFROBOT. The ambient air T_A was averaged between the two sensors and the top sensor measured the temperature PLA temperature T_{PLA} as it was extruded. The second sensor measured the PLA temperature after it went through the fans as a second check to ensure that the fans were not becoming too cool. If the second sensor measured that the extruded PLA was becoming too cooled, it would reduce the fans' speed regardless of what the main controller and equations determined.

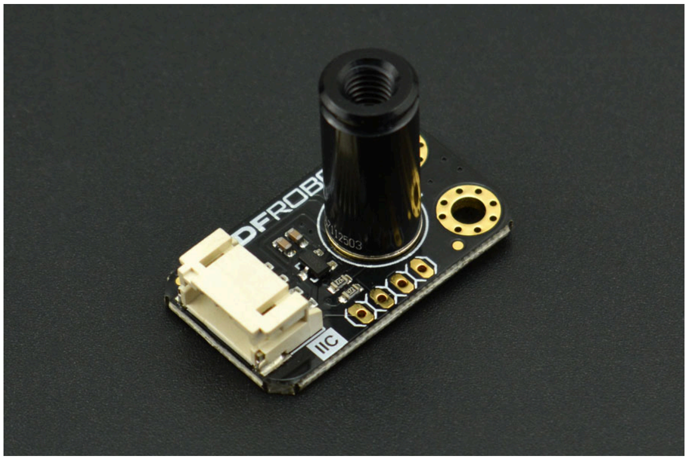


Figure 5: The Gravity: I2C Non-contact IR Temperature Sensors (MLX90614-DCI) from DFROBOT.

The thickness L of the material was measured by the camera and sent to the cooling controller in live time. The cross-sectional area A was calculated to be L * 0.04 where 0.04 was the length that the fans blew onto the PLA as it extruded at one time. Also, the fact that two fans were used was taken into account at the stage where the calculated CFM was converted into a value from 0 to 255 which was the range that had to be sent to the fans in order to change their speeds. The material's thermal conductivity k was researched online and appeared to change depending on the temperature of the PLA. As such, we choose to start with the value 0.111 W/(m·°C) which is the value for PLA at 48°C (PETG vs PLA - Matmatch). This was not a perfect value since our PLA was a lot warmer, but it was a good starting point since it gave us a good range of where the values could be and we tested different values around that one to find better results for the cooling of the extruded PLA. The cooling controller was adjusted several times after its initial implementation in order to find the optimal values for keeping the PLA at the desired temperature of approximately 65°C. This was done so that the extruded PLA could be spooled effectively without snapping or becoming misshapen so that it could be recycled for future printing.

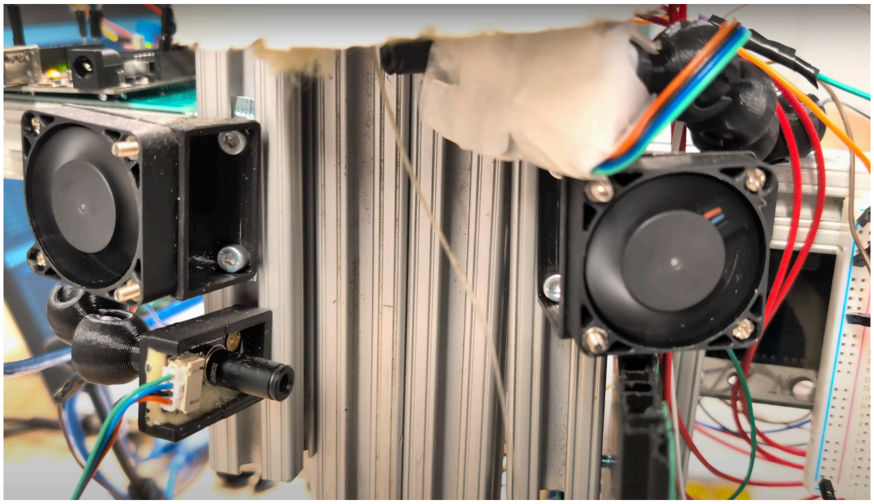


Figure 6: The cooling system that is placed right under the extrusion nozzle.

The system has two 40mm GeeekPi PWM Controllable Fans and two DFROBOT Gravity: I2C Non-contact IR Temperature Sensors (MLX90614-DCI). One of the temperature sensors is above the fans and the other is below the fans. The fans each have 3D-printed ducts on the back side of them to help focus the airflow on the extruded PLA.

Measurement

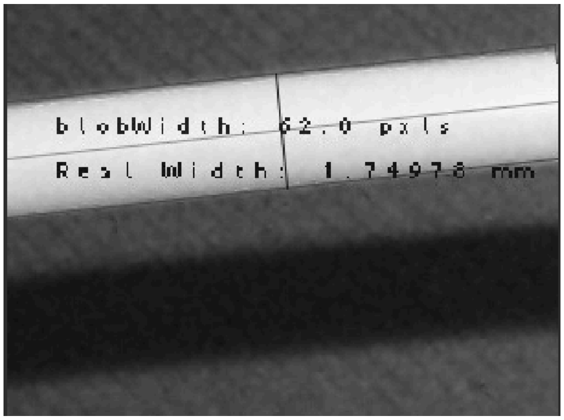
Once the filament is extruded the output's diameter is measured using an OpenMV H7 plus camera. Our choice of using an H7 plus with a resolution of 2952x1944 (5MP), instead of the standard H7 camera at 640x480, allows the image frame to contain more pixels, making our reading far more accurate.

Onboard the OpenMV camera is a machine vision program that utilizes canny edge detection in order to identify the edges and calculate the width of the PLA.

The edges are identified through the openMV camera through the find_blobs detection algorithm built into the OpenMV library. By setting color thresholds based on the grayscale output of the PLA, the program identifies the edges that make up the PLA stand in image view. By subtracting the average value of the pixel distance between the highest and lowest y-axis values we can solve for the width of the PLA.

$$width = (lensDiamter \,/\, frameWidth) * averagePixelWidth * error$$

This takes the OpenMV camera length in mm, the length of the image frame in pixels, and the solved average width from the find_blobs algorithm. To refine this value we can place a PLA sample of known width and adjust the error value until the reported value matches the known width. The OpenMV idea also allows us to natively set thresholds based on an image file or the current image frame, so further adjustments are made simple when necessary.



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blobWidth: 62.0 pxls
Real Width: 1.74978 mm
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Figure 7: Measurement of the PLA using the OpenMV camera including the pixel count and real world millimeter measurement.

To ensure that our set threshold values remain consistent the OpenMV camera is contained in a box preventing external light while the built-in LED on the OpenMV is switched on to provide light onto the measured PLA.

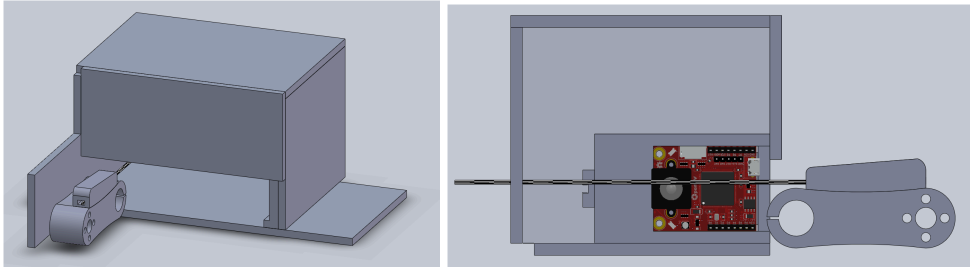

Figure 8: The CAD diagrams of the box containing the OpenMV camera.

Power Supply

Overall the system was connected to a 12-volt AC to DC plug which directly supplied power to our Arduino main board and the extortion auger's stepper motor. The Arduino board is most effective when inputted with 7 to 12 volts (*Arduino - Mouser*), while the Nema 23 stepper motor takes 10 to 30 volts. The cartridge heaters use 24 volts so a separate 24-volt power supply is used to power it through the Relay Switch.

Control

The system is mainly controlled with the use of 3 Arduino boards, two Arduino Megas, and one Arduino Uno. The Uno board houses code for controlling the heat cartridges and reading the thermistors. The first Mega board controls the extruder and winder. Finally, the second Mega board takes in data from the two other boards, and the OpenMV camera using these values adjusts fan speed, winder speed, auger speed, and heater temperature to ensure the PLA remains consistent in diameter. To keep track of our code we maintained a GitHub repository (*WPI-PLA-MQP/PLA-Recycle-MQP*, 2023/2023).

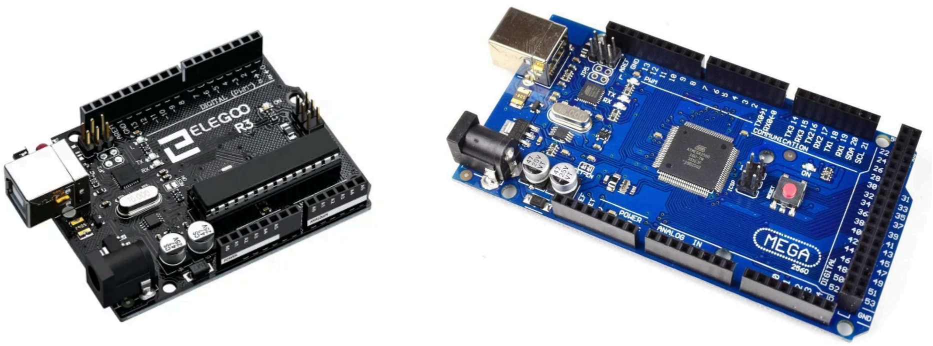

Figure 9: Arduino Uno (right) and Mega (left) Boards

Conclusion

Our team created this system to construct an affordable and space-constrained PLA recycler in order to help reduce PLA waste by re-spooling unneeded PLA for reuse. We were able to get a largely consistent strand of 1.00 millimeters thickness PLA spooled for approximately 20 meters of length. From there we tried to improve the system to achieve a thickness closer to the desired 1.75 millimeters and were able to extrude PLA approximately at this thickness for brief periods of time but it did not stay at that thickness for very long. This was due to several factors, mainly that gravity was pulling the plastic down and thinning it before it was cooled and spooled since it had more mass at this thickness than the 1.00-millimeter thick ones did as they were extruding. Although we were not able to extrude the desired thickness for the PLA within the area constraints, we do believe that based on our results, it is possible to achieve this in the future with careful planning and mindful consideration of our recommendations.

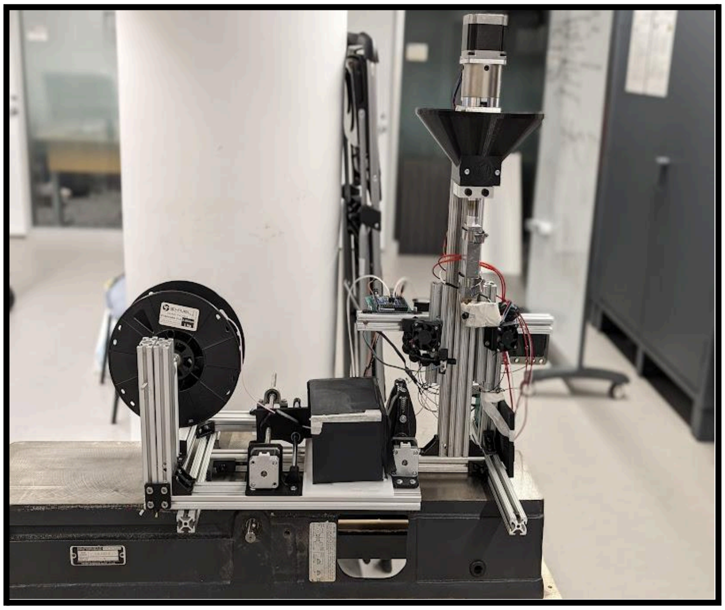

Figure 10: The Final Structure of the Design.

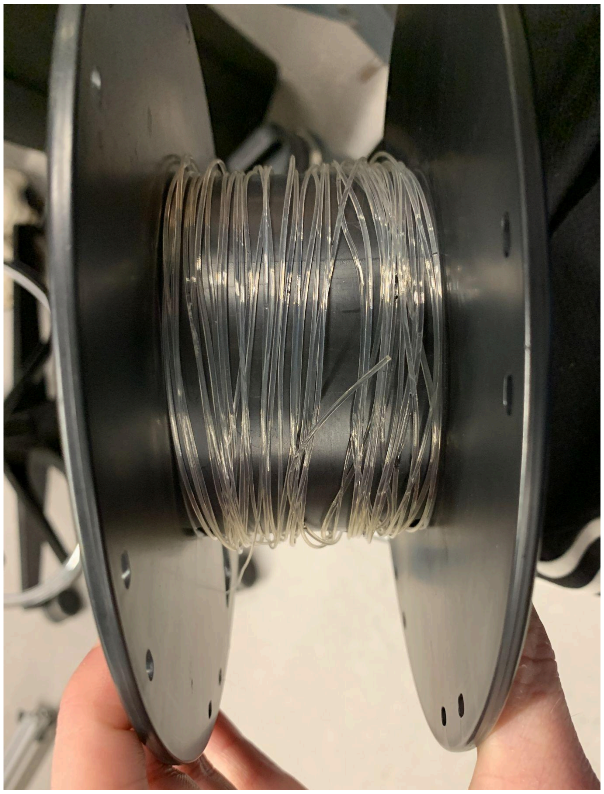

Figure 11: The spool of the extruded 1.00 millimeter thick PLA.

Recommendations

With our time spent on this project, we established several design recommendations that may be vital to others who hope to build upon our work. Our major recommendation being to reduce the influence of gravity on PLA extrusion. Our current system exudes PLA directly from the hopper in a vertical orientation. As so during extrusion the PLA is pulled down by gravity and exudes far faster then we would like, while presenting us with very few methods of slowing extrusion down outside of both slowing down our winder and extrusion auger. Unfortunately when this occurs the output PLA is much less consistent in output diameter. Future implementation would be advised to set the extrusion at least at an angle if not completely horizontal.

In terms of ensuring we have much more control of our PLA output, enclosing the extrusion output and being able to control the ambient temperature of this area may allow for greater consistency in PLA output diameter. In operation, we found that area to be extremely pivotal to how our extrusion spool turned out as this was where the PLA was initially extruded and cooled. The rate at which these both occur can have substantial impacts on end output. One example is that faster extrusion creates a buildup of PLA in that area, paired with slow cooling the extruded PLA becomes bulky and tangled.

Figure 12: Extruded Tangled PLA Strand

In terms of less prioritized, but still significant additions, we would recommend one change and two additions. A faster method of heating within our melting process would be recommended. Very often time was spent waiting for the chamber to reach our desired temperatures. By insulating the space we can increase the speed at which the temperature rises, but a faster rate would be recommended for casual operation. The two additions would be a shredding and drying station as this was out of scope for this project. During operation external devices were used to crush up and dry the recycled PLA pieces, but by adding this to the station we can ensure stable production of recyclable PLA scraps.

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Appendices

PLA Recycle MQP GitHub Repository Link: https://github.com/WPI-PLA-MQP/PLA-recycle-MQP