Developing Strategies for Managing 3D Printer Waste: Extruding and Spooling Polylactic Acid

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Abstract

3D printing is an important tool in educational institutions with a variety of uses and benefits. The most commonly used material in 3D prints is polylactic acid (PLA), a thermoplastic polymer. 3D printing by nature produces a lot of waste material. As plastic waste production continues to rise with severe environmental consequences, the search for methods for recycling plastics becomes more and more pressing. In the last few years, both commercial and open-source systems have emerged for specifically recycling 3D printer plastic. Many of the commercial systems have not yet been perfected and are too expensive for most individuals, hobbyists, and even small university programs. The open-source solutions are complicated, time consuming, and still require a substantial financial investment. In this study, we use ideas from open-source designs to create a preliminary spooling system for turning PLA pellets into spooled filament. The automated system we built costs less than $100 compared to the leading commercial recycling spooling system created by Filabot which costs $3,032. The automated spooling system we created produces filament with a standard deviation in diameter of 0.078 mm, whereas manually spooling the filament gives a standard deviation in diameter of 0.49 mm. Further studies are necessary to perfect the system to produce filament from PLA waste that can be reused in a 3D printer.

Keywords: 3D printing; plastic waste; polylactic acid; recycling; extruding

Background/Introduction

In the 1980s, the first methods were developed and published for the process of 3D printing, also known as rapid prototyping or additive manufacturing. (Pîrjan & Petroşanu, 2013) The original intention of 3D printing was a method that would allow for faster, more efficient prototyping of plastic parts for engineers, rather than sending designs to a facility to create molds to produce the plastic models, wait 6-8 weeks for the product to be returned, and then make small corrections and sent the designs back. Over the next few decades, the applications and popularity of 3D printing expanded greatly. Today, 3D printing can play crucial roles in applications including education, prototyping and manufacturing, medicine, construction, and art and design.(Sculpteo, 2019)

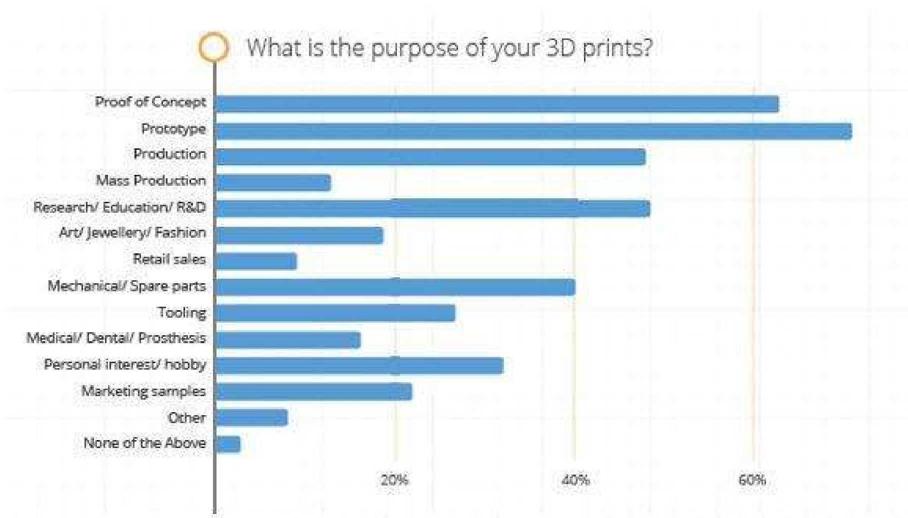

Figure I: Graph of common purposes of 3D printing from "The State of 3D Printing". (Sculpteo, 2019)

3D printing starts with modelling. Models are created using computer-aided design software programs. The model files are then processed by another software program called a "slicer" which creates a new file with instructions for the 3D printer called "G-code." The printer uses the G-code to create the 3D model by adding material layer by layer.(Shahrubudin et al., 2019)

There are several types of 3D printing, the most commonly used is fused deposition modelling (FDM), which is the method that will be focused on in this study. There are a variety of materials that can be used with this method. This study uses polylactic acid (PLA), the most common 3D printer plastic.(Shahrubudin et al., 2019) In FDM, the material is heated and extruded through a nozzle onto a build plate. Plastic is added layer by layer in response to the instructions of the design file.

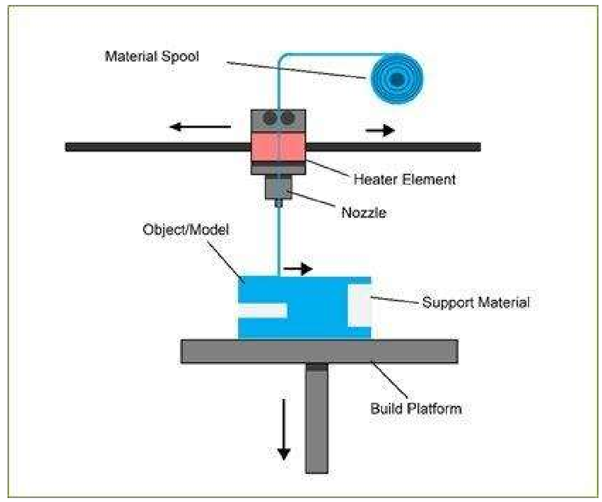

Figure II: Image showing how 3D printing works from https://www.artstation.com/artwork/dzlzWog-post/fdm-fused-deposition-modeling/

The nature of 3D printing makes it a significant producer of waste. For one, prototyping, the leading use of 3D printing, usually results in several iterations of one design with improvements between each print. Every version of the model that is not the final one becomes waste material. Also, designers and printer users often make errors in printer settings or their models. Some of these errors cause the print to fail during or after the printing process. Perfect models also produce waste. Support material, shown in figure II, is used to hold up overhanging areas of prints. When the print is finished, the support material is discarded.

Challenges in Recycling Filament

In 2019, global plastic production reached around 368 million metric tons per year and is predicted to continue rising. (PlasticsEurope (PEMRG), 2019) As more plastic is produced and more waste threatens the environment, it becomes increasingly important to create methods to recycle plastics. Unfortunately, several factors make recycling plastic 3D printer filament waster very challenging. The diameter of the filament must remain within a small range throughout the spool. The ideal filament tolerance in the industry is +/- 0.05mm with an acceptable range of +/- 0.1mm. (Cardona et al., 2016) Filament outside this range cannot be successfully used in a 3D printer. Environmental factors such as temperature, humidity, pH, O_2 presence, and pressure which are difficult to control even indoors can influence the properties of the filament. (Farah et al., 2016; Jamshidian et al., 2010)

Available Methods

In 2013, the first 3D printer filament recycling system became commercially available from a company called Filabot. This was the time when the 3D printing community was beginning to recognize the environmental impact of 3D printing and the urgent need for solutions. Today, there are more options for filament recycling, however, all of them have limitations. (Woern et al., 2018)

One option is shipping waste filament to a facility. A company called Terracycle does this for $85 for a small 11" x 11" x 20" box. This option is expensive and uses fossil fuels.

Another option is commercial products for at-home recycling. Filabot, Filastruder, Filafab, and Noztek are companies that sell these systems. Filabot sells a full recycling set-up from $14,400 - $22,700, or just a spooler and an airpath for $3,500. Not only are these options expensive, but they lack a reliable way to measure the diameter of the filament during the process. Monitoring the diameter is essential to ensure it stays within the small 0.05mm tolerance range. These companies do not usually make a claim about the range in the diameter of the filament that there machines produce.

The third option is option is open-source recycling systems. Hobbyists as well as professionals, universities, and students publish plans and instructions to create at-home recycling systems. These systems are generally lower in cost. However, they also require machining experience or sometimes specialized equipment and tools. The RepRap Recyclebot is an open-source system designed by the Michigan State University Open Sustainability Technology Research Group.(Woern et al., 2018) Their model produces filament from virgin PLA pellets mostly within the +/- 0.05mm with a maximum deviation of +/- 0.08mm. The filament is within the range to be used in the 3D printer. The main drawback to the system is the lack of automation. The user manually adjusts the speed of the system which controls the diameter of the filament.

Another open-source design, the Lyman extruder, has an automated mechanism to adjust the speed in response to the diameter of the filament.(Lyman, 2014) This setup was created by a hobbyist who is a retired manufacturer of lab equipment, and a colleague who is a professor of electrical engineering. Thus, the recreation of this system requires some machining and electrical experience.

3D Printing: Warren Wilson College

The Creative Technologies Lab at Warren Wilson College, a small college in North Carolina, uses 3D printers on almost a daily basis. The lab collaborates with staff, faculty, and students to print objects for art and sculpture courses, math visualizations, GIS maps, and other miscellaneous items. PLA waste is produced through these processes from support material, prototyping, educational prints, and experimentation. To better align with the college's mission of sustainability, a system is needed to recycle the waste that is produced in the lab.

The steps for recycling filament include preparing the plastic, extruding and spooling. Preparing waste filament involves cleaning, grinding, and filtering to produce uniformly sized pieces to be extruded. For this study we used purchased, virgin PLA pellets.

In 2014, the lab purchased a grinder (model number P1060492s) from Filastruder and an extruder (model number FOEX2-110) from Filabot to recycle waste filament produced in the lab. The grinder shreds the plastic waste, which is then put in the extruder to be melted then extruded through a nozzle. At the time, Filabot, nor any other companies sold a spooler to go with the extruder. Once the lab began using the extruder, they quickly ran into difficulties with the produced filament. The warm filament would leave the extruder nozzle, and fall towards the ground. Gravity caused the warm filament to stretch producing a variable diameter. A system was needed to maintain a consistent diameter of the filament and to wind it onto a spool so it could be used in the 3D printer again. This was done by adapting methodology from the RepRap Recyclebot and Lyman's open-source designs for spooling systems. (Lyman, 2014; Woern et al., 2018)

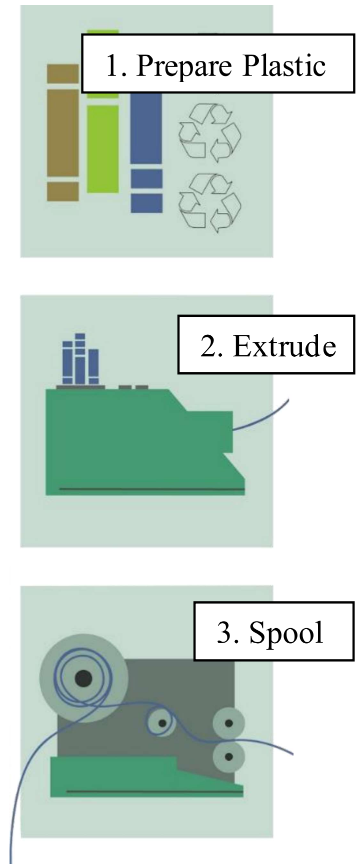

Figure III: Steps for recycling 3D printer filament from Filabot.com

The objective of this study was to create a spooler with a diameter-sensor feedback system to spool filament coming out of the extruder. We then evaluated the feedback system and compared the consistency in the diameter of this filament to the consistency of filament spooled manually.

Materials and Methods

Introduction

We constructed the recycler using a combination of purchased, 3D-printed, and various repurposed parts. The system consists of a grinder, extruder, and spooler. The grinder and extruder were purchased components. The creation of the spooler was the primary focus of this study. We programmed a Raspberry Pi computer to control the system. All designing and modelling of 3D-printed parts was done in the 3D CAD software program Fusion360. (*Fusion360*, 2020)

Our methods followed the methods of the RepRap Recyclebot, as well as Hugh Lyman, a hobbyist and designer whose full, detailed material and methods are open-source online. (Lyman, 2014; Woern et al., 2018) We used the filament width detection method used by both Lyman and the RepRap Recyclebot an optical micrometer developed by Filip Mulier.

Components

The system consists of six primary components. The extruder, four fans, an optical micrometer, tension rollers, a motor attached to an empty spool, and a Raspberry Pi computer.

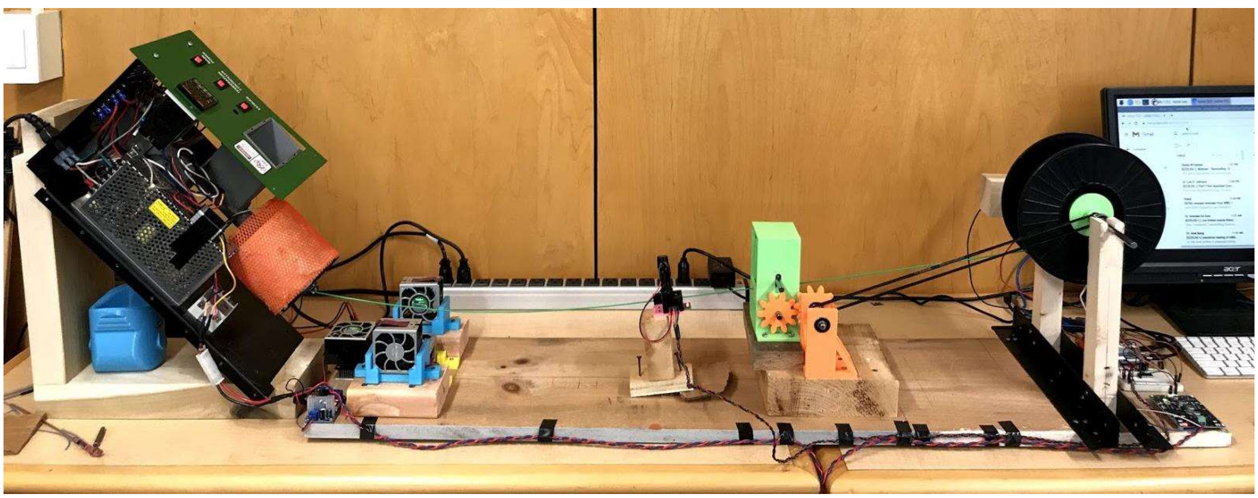

Figure IV: Automated spooling system

The extruder (figure V) was purchased from Filabot in 2014. It was mounted on a wooden frame at a 45-degree angle. This frame was partially designed and fully built by Jeremy Epstein, a WWC Fine Woodworking Crew member. A funnel was designed and 3D printed by Sophia Rowe, a WWC Tech Lab Crew member and attached to the top of the extruder in the opening where filament is placed to be heated. Filament is heated to 200 degrees Celsius. It is then pushed through the nozzle with an augur and extruded in a thread-like form.

The four fans are placed directly in front of the extruder. Two are resting on heat sinks and face upwards. The other two are mounted on wood blocks and 3D printed fan mounts and face towards each other. Three of the fans are powered with an external power source (model Extech 382275) with seven volts of power. The fourth fan is powered by the extruder, which is plugged in to an outlet. The voltage is kept at seven volts using a manual potentiometer.

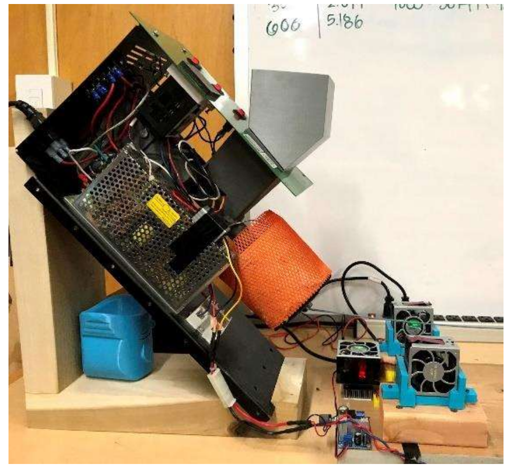

Figure V: Extruder with 3D printed funnel (gray)

The optical micrometer in line with the fans about 30 cm away in the direction of the spool (figure VI). It was developed by Filip Mulier as a filament width sensor. It shines an LED light in a closed box which the sensor passes through. It records the amount of shadow and outputs a corresponding amount of voltage that is recorded using the Raspberry Pi.

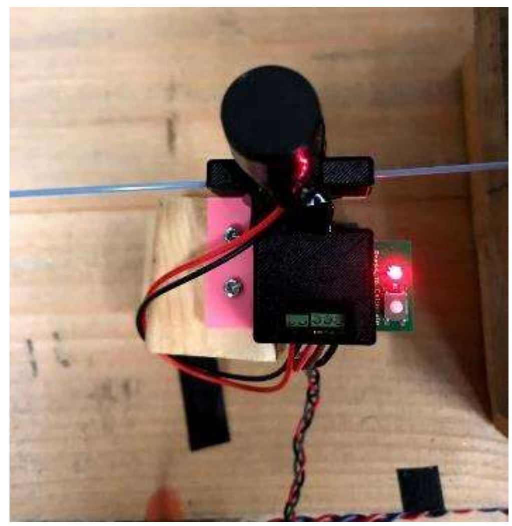

Figure VI: Optical micrometer sensor donated by Objects with Intelligence

The tension rollers are modified designs of Lyman's open source stl files. We remodeled all of the components make them compatible with our system. We printed cylindrical rollers and wrapped them in three layers of soft neoprene cut out of a recycled lunch box, secured with electrical tape. We covered each with a section of used bike tube to prevent the filament from sliding. We added gears on each of the rollers to ensure they turned smoothly towards each other (figure VII). The two rollers were mounted in a shell with 8mm rods. The bottom roller was mounted on an 8mm rod and bearings that were set into the shell. The top roller has a second inner shell covering the top and its two sides with bearings mounted in this shell. The outer shell has 35mm oval cut-outs where the rod could move up and down as needed. A spring was placed between the inner and outer shell held in place by a raised, circular knob on each of the surfaces to keep tension between the rollers. A gear was 3D printed and attached outside of the mounting box to the rod. The gear was placed up against an identical gear on a different 8mm rod. A 20-toothed gear (model 500212-US1) was secured to this rod. The gear was attached to a gear on the spooler using a toothed, rubber belt.

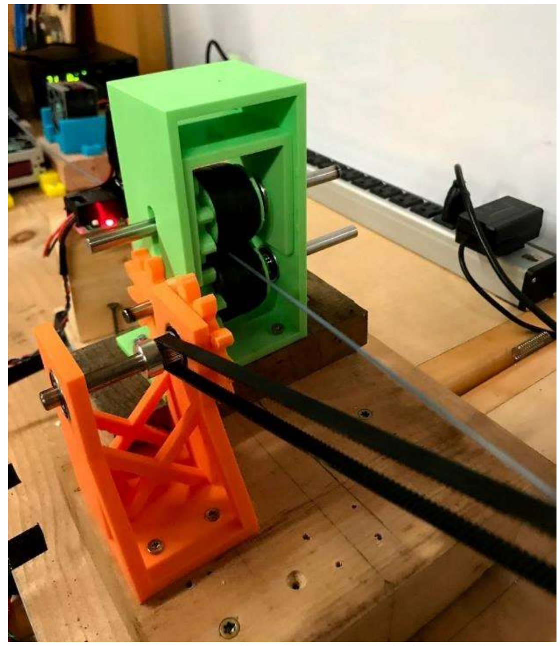

Figure VII: Tension rollers (green) with box and gear (orange) for turning directionality with belt.

The empty spool is secured by two, 3D printed pieces that are placed through the empty spool, meeting in the middle and screwing into each other (figure V). One piece has a gear on it that has a 1:5 gear ratio with the gear on the motor. An 8mm rod was placed through the spool and spool pieces and held in place using set screws. The gear corresponding to the ones used in the tension rollers and worm gear was attached to the rod as well. Bearings were attached on the outer portions of the rod and set into pieces of wood. Jeremy Epstein built the mount which consisted of two pieces of wood on either side of the spool

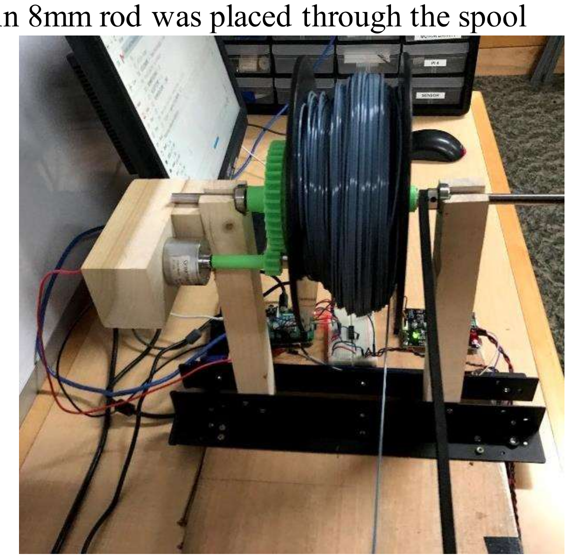

Figure VIII: Spool, wooden mount, motor, motor and spool gears.

connected to the base board with recycled metal brackets. A third piece of wood was attached using wood glue to the side of the spool with the gear piece. A hole was drilled in the piece of wood for the 12V DC motor (model). A 3D printed gear was attached to the motor and lined up with the gear on the spool. A positive and negative wire were attached to the back of the motor.

Wiring and Software

The Raspberry Pi was used with a monitor and ethernet cable to the left of the spooling system. The Raspberry Pi was connected to the breadboard, motor driver (model number PN00218-CYT12), and diameter sensor (figure VI). The motor was powered by the extruder which was connected to the motor driver. The sensor was powered by 5V from the Raspberry Pi. A program was created using Python programming language and Mu software. The program started the 12V motor at 40% of its maximum power. The program has several global variables that can be easily changed by the user including the desired filament diameter, the tolerances, how often readings are taken, and how many readings are taken before taking the mean. For this study, while the program was running, a diameter reading was taken every 0.01 seconds from the sensor. After 50 readings had been taken, the program took the mean of the readings. If the mean was greater than desired, the motor would speed up, stretching the filament and giving it less time to cool before reaching the spool. If the mean of the widths was less than desired, the motor would slow, giving the filament more time to cool before

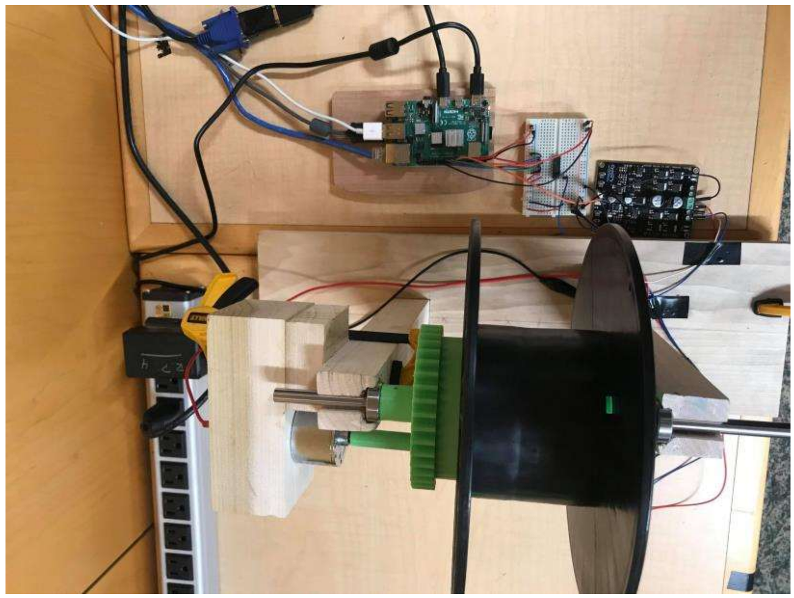

Figure IX: Spool, computer, motor, and motor driver reaching the spool. After each cycle through the program, the mean of the readings, the speed of the motor, and the amount of time passed were saved to a file on the computer, and the diameter and motor speed were displayed to the user. The amount of change in the speed of the motor was dependent on how far away from 1.75mm the filament was. If it was greater than or equal to 0.2mm, the speed adjusted by 0.5% of the maximum power. If it was between 0.15 and 2.0mm, it adjusted by 0.2%. If it was between 0.1 and 0.2mm, it adjusted by 0.1%. If it was between 0.05 and 0.1, it adjusted by 0.05%. If it was between 0 and 0.05, the speed of the motor did not adjust.

Running

One kilogram of virgin PLA pellets purchased from Filabot are placed in a plastic bag with one packet of color concentrate purchased from 3DXTech (SKU BL6-UNI). The pellets are mixed thoroughly. 100 grams of this mixture are placed in the funnel into the extruder. The extruder is turned on and set to heat to 200 degrees Celsius. The external power source is turned on and set to seven volts to power three of the fans. When the extruder reaches 200 degrees, extruding is turned on. When the first melted PLA comes out of the nozzle, it continues to fall onto the table untouched for about 30 seconds. The first approximately 30 seconds of extruded filament is generally visibly low in quality. (Soedira et al., 2020) After 30 seconds, the string of filament is cut using scissors, and is then manually pulled through the system. It is carried over the fans and threaded through the sensor case. The two methods of spooling compared in this study are manual, using just the fans, sensor, and empty spool (without the motor) and automatic, using all components of the system created.

For the manual method, after the filament goes through the sensor case, it is gently pulled around the spool, starting from the bottom and circulating back towards the system. The end is taped to the spool with a small piece of electrical tape. From there, a program is started in

Raspberry Pi that takes a reading of the diameter from the sensor every second and displays it to the user and prints it to a file. The person operating the system turns the spool as smoothly as possible, watching the diameter readings and trying to adjust accordingly.

For the automatic method, after the filament goes through the sensor case, it goes between the tension rollers, then onto the empty spool where it is attached with electrical tape. The program is started in Raspberry Pi and the speed of the motor adjusts automatically in response to readings from the sensor.

Data Collection and Analysis

The objective of this study was to produce filament within the diameter range that could be used in the 3D printer, 1.75 ± 0.1 mm. Thus, our assessment analyzed the diameter of the filament using the readings obtained using the sensor.

The data saved from the raspberry pi was converted from a text file to a CSV file, then imported into R. R was used to create scatterplots, histograms, density plots, and to find the statistical significance comparing the two methods. The standard deviations of the diameter using each method were calculated to numerically represent the consistency of the filament. The percentage of diameter readings that were within the range of compatibility was also taken for each method.

The rotations per minute were estimated using a calibration curve. A marker was placed on the outer edge of the spool and the motor was run at 30% of its maximum power. The number of rotations was measured by using a protractor and referencing the marked spot. The motor was then run at 60% of its maximum power and this analysis was repeated. These two data points were used in R to create a model. This model was used to create a new column in the dataframe that included the diameters, time and speed for the automated trial by being applied to the speed column. This model could not be used for the manual trial because the motor was not running and a value for speed was not recorded.

Results

The percentage of filament readings produced that were in the desired range of 1.75mm ± 0.1mm was greater for the automated method than for the manual method. The automated method produced 79.5% (263 of 331 readings) in range, whereas the manual method produced only 20.1% (173 of 862 readings) in range. The standard deviation of the automated method was 0.078, and the standard deviation of the manual method was 0.492. The manual method performed worse using both of these evaluation methods.

A proportion test was done to compare the proportion of readings in range between the automated method and the manual method. The p-value given from this test was $p < 2.2 \times 10^{-16}$. This indicates a significant difference between the two methods.

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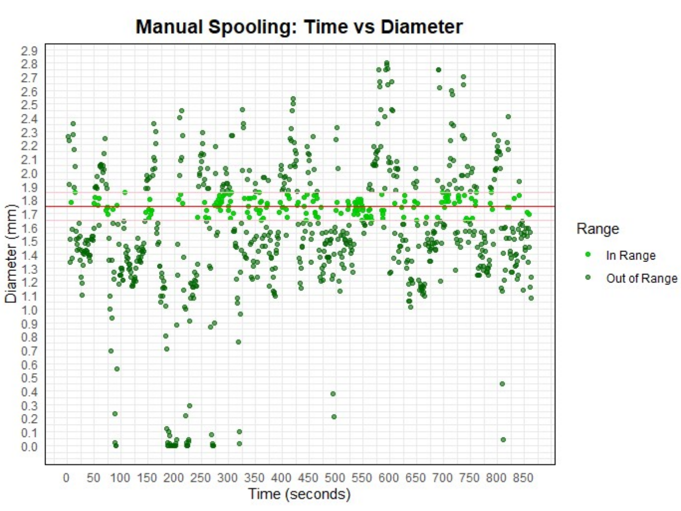
Method	Standard Deviation	Percent in Range
Automated	0.078	79.5
Manual	0.492	20.1

Table I: Table of standard deviations and the percentage of diameter readings within the desired range of 1.75mm ± 0.1mm for each method used.



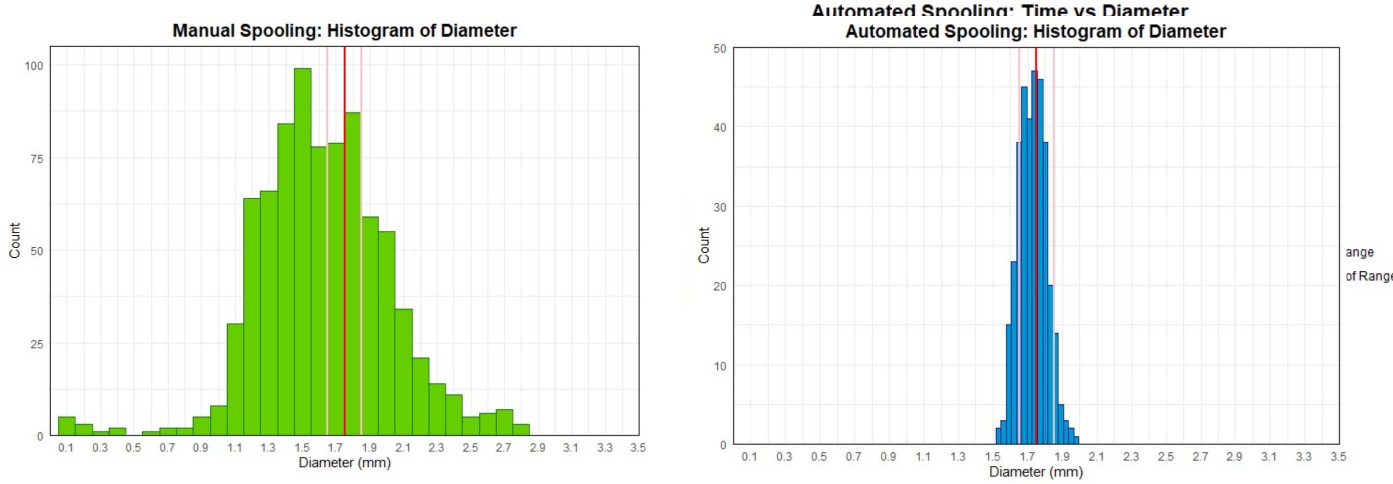


Figure XI: Histograms of diameter in mm. Red line shows desired diameter (1.75mm). Pink lines show limits of diameter range (1.65mm, 1.85mm). A) Manual spooling method histogram of diameter - shows a wider range and less precision. B) Automated method of spooling histogram of diameter – shows a narrower range and less precision.

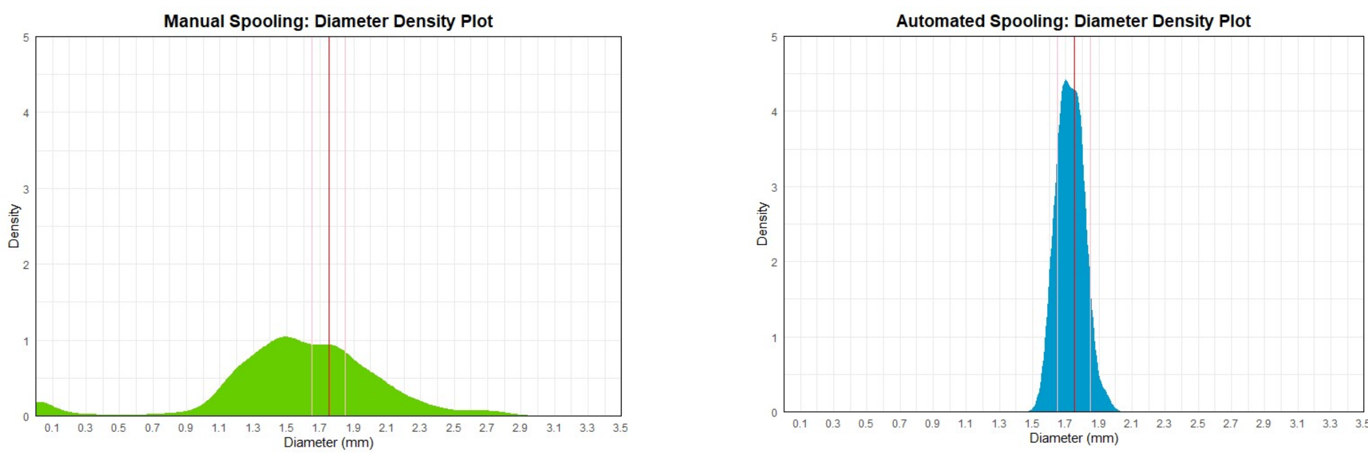


Figure VIII: Density plots of diameter in mm. Red line shows desired diameter (1.75mm). Pink lines show limits of diameter range (1.65mm, 1.85mm). A) Manual spooling method density plot - shows broad range with slight right skew. B) Automated spooling method density plot – shows more precision and smaller range.

Discussion

In this study, we demonstrate the benefits of an automated spooling system compared to a manual spooling system for polylactic acid. The automated spooling system utilizes a feedback technique to control the speed of the motor that is spinning the spool. The speed of the motor is the primary mechanism used to manage the diameter of the filament that is being spooled. This method produced significantly better results ($p < 2.2 \times 10\text{-}16$) than manual spooling for this trial with 80% of the readings being within the desired range compared to only 20% for the manual readings.

The system created in this study differs from other open-source systems in a few key ways. All of the systems vary in the tolerance range of the filament they produce, the experience of the creators and thus the quality and accuracy of the components, as well as the identity of the components in the system.

The RepRap Recyclebot includes a traverse mechanism to evenly spool the filament. It uses the optical micrometer developed by Objects with Intelligence.(Woern et al., 2018) The reading given from the sensor is shown on a control box. The user manually controls the speed of the motor to try to keep the diameter within the ideal range as opposed to an automated adjustment. The filament produced using virgin PLA pellets in this system has a range of +/-0.05 mm with a maximum deviation of +-0.08 mm.

The Lyman Extruder also contains a traverse mechanism and the sensor developed by Objects with Intelligence.(Lyman, 2014) It uses an automated feedback system to adjust the speed of the motor in response to the filament diameter. Recycled PLA is prepared using a pelletizer before it is extruded. The filament it produces is mostly within the +/- 0.1 mm range, but occasionally exceeds this.

The automated system created in this study contained the sensor developed by Objects with Intelligence and automated feedback controlling the motor. It did not contain any type of traverse mechanism as seen in the other two systems. 80% of the filament produced was within +/- 0.1 mm of the desired diameter, 1.75 mm. The standard deviation was 0.078 mm.

Future Studies

The primary focus of future research should be ensuring that 100% of the filament stays within the range. This could be done by refining the system or adding components. The traverse mechanism is a good starting place, based on its use in the Lyman system and the Recyclebot. Several attempts were made to create a worm gear, servo motor, and other options for even spooling. None of these attempts were successful. The designs used for the RepRap Recyclebot traverse mechanism may be modified to work with our system. This mechanism would prevent the spool from having a different number of layers in different places on the spool which causes the diameter of the spool to be variable. Areas with a greater diameter will necessitate a slower rotational speed of the motor in order for the filament to be pulled at the same rate as it would in areas with a smaller spool diameter.

The DC motor that was used was specifically designed to be high torque with low rotational speeds. The speed was further reduced using a gear ratio of 1:5, and the motor was run using about 35 – 45% of the maximum voltage. When powered with the raspberry pi and motor driver board, the amperage was variable and caused the motor to be "skippy" and somewhat inconsistent. This causes the filament moving towards the spool to wobble, possibly pulling in certain areas and thinning it. Changing the gear ratio to slow the motor further may allow the user to use a greater voltage to power the motor making it turn more smoothly.

Further research involving chemical analysis of PLA may also be beneficial to increasing the effectiveness of this system.(Shahrubudin et al., 2019; Farah et al., 2016) A better understanding of the impact of temperature could enable utilization of the heating temperature of the extruder and the power directed to the fan as factors to control the diameter of the filament. The color of the filament also changes the chemical properties and the dynamics of the material and has an effect on the processing of the filament.(Wittbrodt & Pearce, 2015) This should be considered when working with recycled filament of varying colors.

Recycling is the ultimate goal of this system. Designing and creating a pelletizer such as the one used by the Lyman Extruder to make the size and shape of the waste filament more consistent is a crucial next step towards this goal.

Conclusion

This study displays the successes of an initial system for recycling PLA in the Warren Wilson Creative Technologies Lab. Further improvements to the system are needed to produce filament that fits within the diameter range required by the 3D printer. Future studies may include the addition and variation of the components of the system from an engineering perspective, as well as a chemistry-based approach investigating the effects of different factors on the properties of PLA. This research provides an important starting point for future research into the implementation of a PLA recycling system in the Warren Wilson College Creative Technologies Lab.

Acknowledgments

Thank you to Brian Conlan for helping me every step of the way with this project starting three years ago when you introduced me to the world of computer design and programming which became my favorite things. Thank you for encouraging me and believing in me throughout my time here and helping me develop my passion for making things. Thank you to Sophia Rowe for all of the ways you helped me get through this project. Thank you to Jeremey Epstein for always being positive and willing to help with all of the various, last-minute woodworking requests I made. Thank you to David Coffey, my primary advisor for teaching me, helping me, and being patient with me throughout this whole process. Thank you to Thomas Robacker for sharing your enthusiasm and helping me with programming, and to my other committee member, Liesl Erb. Thank you to Filip Mulier who shipped me a $60, out-of-stock sensor for free and enabled me to do this study.

Appendix

Software

The following code was written in Python programming language in the Mu program on Raspberry Pi.

```
import gpiozero
import time
from gpiozero import MCP3008
from time import sleep
#Setup pins
Backward = gpiozero.OutputDevice(23) # On/Off output
Forward = gpiozero.OutputDevice(18) #On/Off output
SpeedPWM = gpiozero.PWMOutputDevice(24) # set up PWM pin.
speedFlag = 260
#diameter range
DIAMETER_IDEAL = 1.75
TOLERANCE1 = 0.05
TOLERANCE2 = 0.10
TOLERANCE3 = 0.15
TOLERANCE4 = 0.20

#file name
FILENAME = "day1testing5_1.csv"
#variables to change
NUMREADINGS = 5
SLEEPTIME = 1
TEMPERATURE = 200

#write initial conditions to file
file1 = open(FILENAME,"a")
print(TEMPERATURE,file = file1)
print(NUMREADINGS,file = file1)
print(SLEEPTIME*10,file = file1)
timepassed = SLEEPTIME

while True:
   #speed
   SpeedPWM.value = speedFlag/1000
   #open file
```

```
file1 = open(FILENAME,"a")
#create empty list
dimlist = []
diameter = (MCP3008(0))
#get diameter value
fulldiameter = diameter.value *5
#add diameters to list
for i in range(1,(NUMREADINGS+1)):
   #dimlist.append(fulldiameter)
   dimlist.append(fulldiameter)
   sleep(SLEEPTIME)
#meanoflist
dimmean = (sum(dimlist))/NUMREADINGS

#if speedFlag can still be adjusted
if speedFlag < 1000 and speedFlag > 50:
   if dimmean >= DIAMETER_IDEAL + TOLERANCE4:
      speedFlag += 5
   elif dimmean >= DIAMETER_IDEAL + TOLERANCE3:
      speedFlag += 2
   elif dimmean >= DIAMETER_IDEAL + TOLERANCE2:
      speedFlag += 1
   elif dimmean >= DIAMETER_IDEAL + TOLERANCE1:
      speedFlag += 0.5
   elif dimmean <= DIAMETER_IDEAL - TOLERANCE4:
      speedFlag -= 5
   elif dimmean <= DIAMETER_IDEAL - TOLERANCE3:
      speedFlag -= 2
   elif dimmean <= DIAMETER_IDEAL - TOLERANCE2:
      speedFlag -= 1
   elif dimmean <= DIAMETER_IDEAL - TOLERANCE1:
      speedFlag -= 0.5
#if speed is max
elif speedFlag >= 995:
   print("Max Speed Reached")
#if speed is min
elif speedFlag <= 5:
   print("Minimum Speed Reached")
#add time
timepassed += (SLEEPTIME*10)
#print mean diameter
print("{:.2f}".format(dimmean))
#print speed flag
print("{:.2f}".format(speedFlag))
#write diameter and speed to file
```

```
   print("{:.2f}".format(dimmean),"{:.2f}".format(speedFlag),"{:.2f}".format(timepassed),file =
file1)
   #close file
   file1.close()
```

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