Machine Testing: Experiments and Results

P20 Filament Spoolers

Autumn 2024

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Contents

Introduction

The purpose of this document is to present the experiments conducted by previous groups that validates each subsystem and the overall assembly for reliability. The results gathered require initial quantitative analysis to and rigorous trial and error approach to understand the similarities between the qualitative observations compared to the theoretical assumptions.

Recommended PPE for All Testing

- Safety glasses or some equivalent

Recommended:

- Long-sleeved shirt and pants to cover from any hazards
- Enclosed shoes always

Cooler System

Experiment 1: Fan Speed Measurement

To determine the speed as well as the direction of the fans across the cooling. Ideally, all fans should have relatively equal RPM to uniformly cool the filament and ensure fan ratings are receiving distributed power requirements.

Experiment 1 Apparatus:

- All Fans (Axial/Blower) required to be used for cooling
- Arduino Uno
- Cooling Trough
- Breadboard and Wires
- Laptop
- Power Supply
- Tachometer

Experiment 1 Method:

An experiment setup is demonstrated in Figure 1

1) Set up the Apparatus and power the fans to their rating requirements (Refer to Figure 1 for reference)
2) Write the code for testing and checking one fan (Refer to Figure 2 for reference)
3) Use the tachometer for record the RPM for the fan (Refer to Figure 4 for reference)
4) Repeat steps 1-3 for all other fans required for testing
5) Dependent on fan specifications, if the fan has a sensor output for RPM tracking, wire it to the Arduino and record up to ten values on the serial monitor output (Refer to Figure 3 for reference)
6) Repeat step 5 for all other fans for testing
7) Repeat Steps 1-3 where all fans are powered simultaneously
8) Record the RPM reading from all fans during simultaneous setup (Refer to Figure 4 for reference)

Experiment 1 Results:

Based on the results, testing the fans individually showed results for three out of four fans tested going beyond their specified fan RPM (> 5500 RPM). The result likely means the fan has drawn beyond its limit, caused by either significant voltage spikes (temporarily) or factor with the component itself. On the other hand, testing multiple fans in conjunction proved to show that there is linear voltage regularity amongst the fans that their speeds are within 5% tolerance. By testing the ranges from two fans in operation to four fans, it is clear that there is no significant difference between the output each fan is receiving. While the readings are given from the fans' inherent sensors, more testing is required to validate the speed controllability. For instance, there was no available tachometer for testing with the experiment. It is recommended that testing with the tachometer is necessary to establish a comparative reading difference between the readings given by the in-built sensor of the fan and realistic observation that occurs during operation. Verifying the fan speed will clarify power distribution designed for the fans, and the necessary speed to cooling ratio such that there is efficient and managed cooling throughout the extruding operation that could cause slight, but inaccurate filament sizing.

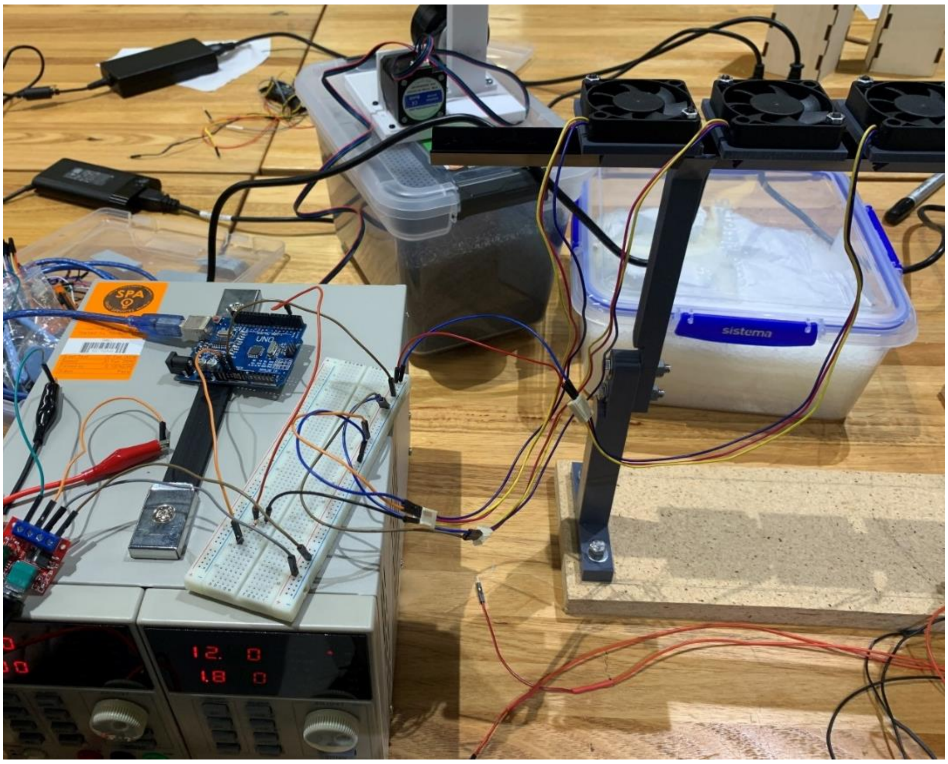

Figure 1: Fan Speed Experiment Setup

```
// ////////////////////////////////////////////////////
// /***** 3-wire fan code *****/
// ////////////////////////////////////////////////////
int count = 0;
unsigned long start_time;
int rpm_reading;

// Setup Serial Rate and Pin
void setup(){
  Serial.begin(9600);
  attachInterrupt(digitalPinToInterrupt(2), counter, RISING);
}

// Loop RPM count every minute
void loop(){
  start_time = millis();
  count = 0;
  while((millis() - start_time) < 1000){};
  rpm_reading = count*60/2;
  Serial.print(rpm_reading);
  Serial.println(" rpm");
}

// Counter
void counter(){
  count++;
}
```

Figure 2: Sample Code for Fan Testing

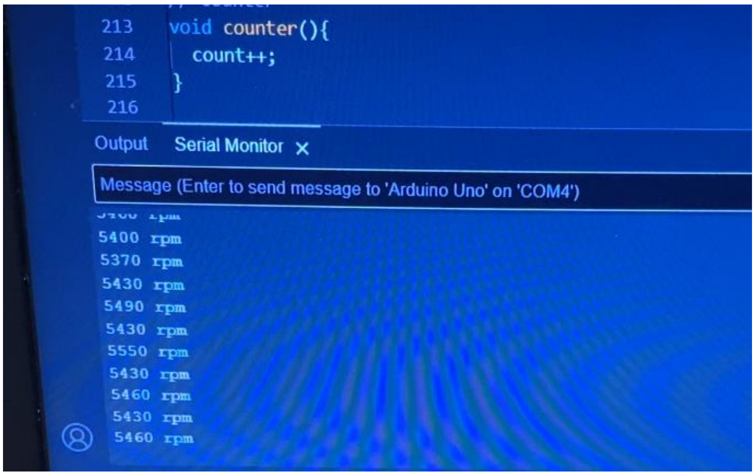

Figure 3: Serial Monitor Output Readings

Experiment 1: Checking All Fan RPM Ratings with Current Configuration

	Fan 1	Fan 2	Fan 3	Notes	Assumptions
Test1 - Single Fan	6398 rpm	6502 rpm	6132 rpm		All wires work
	6188 rpm	6312 rpm	5589 rpm		10220 ohms Resistance
	6188 rpm	5812 rpm	5869 rpm		Parallel circuit
	5798 rpm	5678 rpm	5690 rpm		3.3V supplied to sensor output
	6398 rpm	5945 rpm	5732 rpm		
	5978 rpm	6123 rpm	5643 rpm		
	6548 rpm	5761 rpm	5864 rpm		
	6068 rpm	5689 rpm	5734 rpm		
	6518 rpm	5853 rpm	6067 rpm		
	6368 rpm	6007 rpm	5784 rpm		
Test2 - Multiple Fans	5880 rpm	5640 rpm	5520 rpm	After a minute, it corrects itself. Why?	
	5940 rpm	5400 rpm	5490 rpm	After testing Fan2, faulty connection to pin2	
	5970 rpm	5610 rpm	5520 rpm	Fan3 feels weak from physical observation	
	5970 rpm	5520 rpm	5490 rpm	Fan3 RPM still the same as the rest.	
	5970 rpm	5430 rpm	5520 rpm	These results without PWM	
	6000 rpm	5400 rpm	5550 rpm		
	5970 rpm	5400 rpm	5520 rpm		
	5970 rpm	5430 rpm	5580 rpm		
	5970 rpm	5400 rpm	5580 rpm		
	5970 rpm	5430 rpm	5550 rpm		

Figure 4: Record Results (Excel)

Experiment 2: Cooling Layout for Filament Consistency

To determine if the cooling layout of the fans and trough minimises the expansion/shrinkage rate of the filament extruded. The purpose of the experiment is to examine the behaviour of the filament relative to the cooling setup and transferability from extruder to the tensioning subsystem. The parameters and organisation of the subsystem is vital to establish pre-defined cooling stability and ease of maintenance where cost and additional equipment is efficient. Consequently, the results of this experiment will verify enough sufficiency for the extent of air cooling required for the available extruder configurations or, if an alternative such as water/Peltier cooling should be considered.

Experiment 2 Apparatus:

- Desktop SJ35 extruder
- Fans (Axial/Blower) required to be used for cooling
- Breadboard and Wiring
- Laptop
- Filament of Choice
- Power Supply
- Cooling Trough
- Tensioning Setup
- Calliper (or equivalent filament measurer)

Experiment 2 Method:

1) Set up the Extruder settings and wait till temperatures reach desired value before commencing operation.

Extruder Settings (SJ35) (Change extruder parameters if required):

Mold Heating: 160, **Barrel Heating**: 130, **Feed Cooling**: 50, **Extruder Rate**: 410

2) Line up the cooling apparatus uniformly between the tensioning setup and extruder
3) Set up wiring and powering for the fans
4) Set up desired layout for testing
5) Start the extruder
6) Pull initial extruded filament till the filament is fed through the tensioner
7) Adjust tensioning speed accordingly
8) At the output end of the tensioner, cut a small sample of filament
9) Label the filament using a marker or similar distinguishing attribute
10) Stop the extruder
11) Remove all excess filament
12) Reposition the fans to change the layout of preference
13) Repeat steps 4-12 until all layouts have been analysed

Experiment 2 Results:

From the experiment, four layouts have been tested as demonstrated in Figures 5-8. The purpose of the experiment was to compare concentrated fan cooling and distributed fan cooling to identify noticeable differences in the filament quality. Layout 1 was tested equidistant along the aluminium trough, ensuring flow velocity, direction and pressure from each fan had designated areas where cooling direction was maintained. From this case, interference between cooling sections was managed for the filament to receive orderly airflow. Figure 6-8 are very similar layouts with the exception of positioning. Layout 2 was intended to be spaced equally between the extruder and tensioning to provide unaffected operation in one location whereas Layout 4 was for immediate rapid cooling and Layout 3, leaving the filament naturally elongate momentarily before the next operation. The outcomes from these layouts had small, but considerable physical differences.

Layout 1 was the most effective in filament shrinkage rate sizing at 1.8-1.85mm in diameter. This was likely due to each fan individually cooling without interference, allowing stability for the filament to deform linearly. Layout 2 had inconsistency in filament sizing ranging from 1.7-2.2mm in diameter. An identified cause was the fan closest to the extruder was slightly hot, influenced by the heat radiation of the extruder and performance of the fan will drop. This is evident, displayed by the current draw dropping on the variable power supply in testing.

Layout 3 was also inconsistent; within the first five minutes in operation, the filament was sized down to 1.5-1.6mm however, beyond that time, gradually rose to a 1.6-1.7mm range. As mentioned, this time, all fans started performing worse due to the heat. Layout 4 consequently had the opposite effect. The time difference for the filament to reach the cooling was prevalent enough that it had little impact to the filament. The filament was already deforming (~0.6-0.9) meaning, the filament was naturally shaping itself. It is also worth noting that Layouts 2-4 had high turbulent flow due to being bundled together, resulting in variation across the filament size.

These results provide preliminary understanding of the cooling subsystem architecture. Small discrepancies and layout decision will be required to be factored into consideration to meet consistency and desired filament diameter. There are two unaccounted testing that also need to be analysed. Only two materials have been tested: PLA and flexi ABS. More recyclable material can introduce unexpected outcomes; therefore, layout could depend on material. With this hypothetical aspect, the second factor is having a more modular layout that can be adjusted in respect to the material, relative subsystems and the extruder settings.

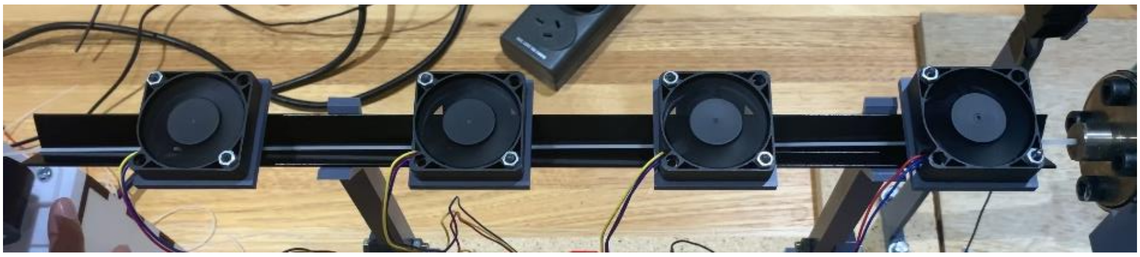

Figure 5: Layout 1 – Equidistant Fan Layout

Figure 6: Layout 2 – Middle Section Focus

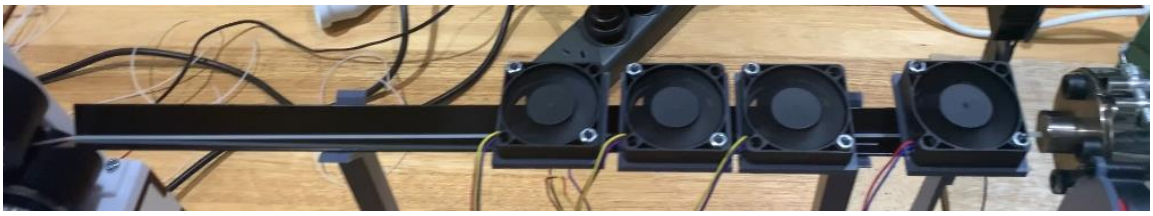

Figure 7: Layout 3 – Extruder Nozzle Focus

Figure 8: Layout 4 – Cooling relative to Tensioning Subsystem

Experiment 3: Temperature Controllability with Extruder Configurations

To determine the temperature changes across the cooling subsystem. The objective of the experiment is to determine the temperature changes between fan cooling across the overall cooling subsystem. Clarifying the experimental results of the temperature changes relative to a preliminary heat transfer analysis of the subsystem will improve the validation of temperature control and optimising the control quality of the filament.

Experiment 3 Apparatus:

- Desktop SJ35 extruder
- Number of Fans (Axial/Blower) required to be used for cooling
- Arduino Uno
- Breadboard and Wires
- Laptop
- Cooling setup ready
- Temperature Gun
- Tensioning Setup

Experiment 3 Method:

1) Set up the Extruder settings and wait till temperatures reach desired value before commencing operation.

Extruder Settings (SJ35) (Change extruder parameters if required):

Mold Heating: 160, **Barrel Heating**: 130, **Feed Cooling**: 50, **Extruder Rate**: 410

2) Line up the cooling apparatus uniformly between the tensioning setup and extruder
3) Set up wiring and powering for the fans
4) Set up desired layout for testing
5) Start the extruder
6) Pull initial extruded filament till the filament is fed through the tensioner
7) Adjust tensioning speed accordingly
8) Use Layout 1 (Refer to Figure 5) to ensure the fans
9) Measure the temperature reading in close and safe proximity to the measured fan
10) Record the reading of the temperature gun (Refer to Figure 9 for reference)
11) Stop the extruder upon recording results
12) Repeat step 9 with all other fans during operation
13) Repeat steps with different fan layout (Refer to Figure 6-8)

Experiment 3 Results:

Upon collecting results, there is variation between temperatures. Taking readings at approximate 0.05, 0.1 and 0.15m away from each fan, the temperature drops were not found linear. It is also difficult to determine the actual temperature upon extrusion as the temperature gun cannot measure off reflective surfaces. Although there is a reference temperature via the extruder settings, it is still unclear as to whether the extruder values are true output values as per in operation. Unfortunately, not enough tabulated data has been collected for this experiment due to time constraints and accessibility to use measuring tools outside of the UTS Protospace facility. Figure 10 is provided for a sample layout in data and part information for calculations. However, it is advised that for improvements concerning the temperature management of the cooling subsystem, that both a heat transfer paper analysis to experimental observation is researched to understand the outcomes of heat dissipation. Furthermore, this concept can introduce temperature control where the cooling system operation correlates to the temperature of the filament, self-adjusting until the diameter from the measurer is maintained.

Figure 9: Temperature Gun Reading

Experiment 2: Fan Positioning and Defining Extruder Settings								
Given	Total current draw	0.84A						
50mm 3 Wire 12V DC Ball Bearing Fan		**50mm Thin (15mm) 12V DC**			**50mm Blower Turbine 12V DC Fan**			
Ventilation Fans		**Ventilation Fans**			This 12V DC Blower Turbine 50mm fan is excellent for cooling electronics, hotends, 3D prints and laser modules.			
type of fan	Axial	type of fan	Axial		Weight	.01 kg		
fan air volume cubic metres	0.33m^3/min	fan air volume cubic metres	0.7m^3/min		Dimension	3 × 3 × 1 cm		
fan air volume cubic feet	11.6ft^3/min	fan air volume cubic feet	23.8ft^3/min		Specifications:			
fan RPM	5500RPM	fan RPM	5500RPM		Rated Voltage: 12V DC			
fan noise	31dB	fan noise	30dB		Rated Current: 0.13A			
fan bearing type	Ball	fan bearing type	Sleeve		Revolution: 5000 ± 10% RPM			
fan housing material	Fibreglass Reinforced Plastic	fan housing material	Plastic		Noise: 25 dBA			
fan impeller material	Fibreglass Reinforced Plastic	fan impeller material	Plastic		Wind speed: 1.5 M/s			
Fan Operational Life at 25°C	100000hr	Fan Operational Life at 25°C	60000hr		Air volume: 4.59 CFM			
fan number of wires	3pc	fan number of wires	2pc		Bearing: oil bearing			
fan connector type	Flyleads	fan connector type	Flyleads		Expected life: 30000 hours			
Power from Plugpack		**Power from Plugpack**			Size: 50mm x 50mm x 15mm(L x W x H)			
Item Connection	Flyleads	DC Plugpack Voltage	12V					
DC Plugpack Voltage	12V	DC Current Draw	190mA		**Metal Mate 20 x 20 x 1.5mm 1m Aluminium Equal Angle - Silver 1m**			
DC Current Draw	130mA	Product Mounting			Lightweight and easy to work with			
Product Dimensions		**Product Dimensions**			Easy to drill, rivet, screw and cut			
Length	50mm	Length	50mm		Adds strength and rigidity to joins			
Width	10mm	Width	50mm		Alloy 6063/Temper T5			
Height	50mm	Depth	15mm					
Packaged Dimensions		**Packaged Dimensions**			Metal Mate aluminium equal angle (L shape) is lightweight and easy to work with, available in a variety of widths and thicknesses in 1 and 3 metre lengths.			
Packaged Volume	0.12675l	Packaged Volume	0.13464l		Equal Angles are available in a mill finish, brushed silver, bronze, black or white powder coated.			
Packaged Weight	0.038kg	Packaged Weight	0.04kg		Suitable for use in general repair and maintenance around the home, including DIY tasks such as making brackets, supports, edge protection, trims for tiling, windows, and doors.			
Packaged Length	6.5cm	Packaged Length	6.8cm					
Packaged Width	6.5cm	Packaged Width	6.6cm		Dimensions			
Packaged Height	3cm	Packaged Height	3cm			Width	Height	Length
		Mounting Method	Through Hole		Product	20mm	20mm	1000mm
					Package	20mm	20mm	1000mm
					Assumptions:			
					We'll assume steady-state conditions for simplicity.			
					We'll consider the filament as a cylinder for the purpose of calculating convective heat transfer.			
					We'll use the Nusselt number correlation for flow over a cylinder to estimate the convective heat transfer coefficient.			

Figure 10: Preliminary Heat Transfer Analysis and Part Parameters

Measuring System

Experiment 1: Consistent Accurate Readings for Different Material

To ensure the consistency and accuracy of light measurements from the laser and the light intensity sensor, it is essential to test the system using freshly made filaments. However, we will use filaments that is premade and pulled through the measurement systems as this provided a controlled environment to assess how well the laser's light interacts with the filament material. This testing is essential to verify that the laser and light sensor accuracy while maintains its specified performance criteria, such as the wavelength and power output, when interacting with different materials, thereby ensuring reliable and precise readings.

Experiment 1 Apparatus:

- 60cm of different filaments (PLA, ABS)
- Laser pointer
- Light Sensitivity Sensor

Experiment 1 Method:

1. Arrange the experimental setup as illustrated in Figure 12. Ensure all components are correctly positioned and securely mounted.
2. Set up the code as shown in Figure 13. Ensure that all parameters are accurately inputted, and that the library is fully UpToDate.
3. Gently pull the premade filament through the designated opening in the setup, ensuring the laser directly hits the filament. This alignment is crucial for accurate data capture.
4. Record the data as the filament interacts with the laser. Ensure that the data acquisition system is properly calibrated and running smoothly to capture accurate readings.
5. Repeat steps 2 and 3 for each type of filament.

Experiment 1 Results:

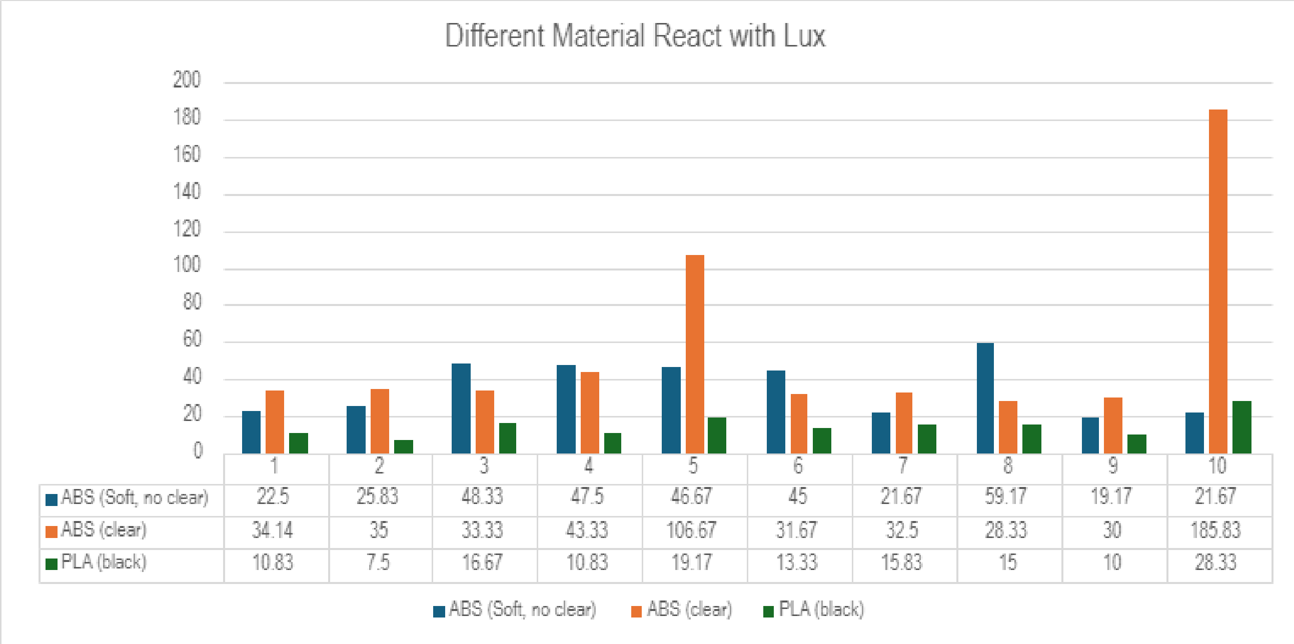

Figure 11. Results of experiment 1

Based on the result of the graph above, there is a clear different in the light reading as different materials property corresponded to different light levels. The three materials that were used are ABS-clear, soft and non-clear as well as PLA which all have different density and properties. From the experiment conducted, we can see the clear ABS have the highest reading of all which is around 30 lux. This is due to its property which means materials with higher transparency allow more light to pass through more. This cause the reading to be higher when comparing with other materials.

When looking at the reading for the other materials, like non-clear ABS and PLA, they have denser property which make them less transparency. Therefore, making them have a low reading then the clear ABS of 21.67 lux for non-clear ABS and 15 lux for PLA. This verified how material parameters are greatly affecting the light intensity measurement by the density, material property and the transmission capabilities. Therefore, we recommend testing different material first and getting the parameters for accurate measurement.

Figure 12: Laser-sensor setup

```
#include <BH1750.h>
#include <Wire.h> // Library for I2C communication
//#include <LiquidCrystal_I2C.h> // Library for LCD
BH1750 lightMeter;
//LiquidCrystal_I2C lcd = LiquidCrystal_I2C(0x27, 16, 2);
void setup() {
  pinMode(2, OUTPUT);//laser
  Wire.begin();
  lightMeter.begin();
  Serial.begin(9600);
  //lcd.begin();
  //lcd.backlight();
  //lcd.setCursor(0,0);
  //lcd.print("BH1750 Test");
 // lcd.setCursor(0,1);
  //lcd.print("Please wait...");
  delay(3000);
  //lcd.clear();
}
void loop() {
   //lcd.clear();
   //lcd.setCursor(0, 0);
   //lcd.print("Light Intensity ");
   //lcd.setCursor(5, 1);
        digitalWrite(2, HIGH);//laser
      delay(700);
   float lux = lightMeter.readLightLevel();
   //float diameter = pow((835.9/lux), (1/5.05));
   //float diameter = -6.16*pow(10, (-3))*pow(lux, 3) + 1.24*pow(10, (-4))*pow(lux, 2) - 0.0242*lux + 2.58;
   //lcd.print(lux);
   //lcd.print(" Lux");
   Serial.print(lux); Serial.println(" lux");
   //Serial.print(diameter); Serial.println(" mm");
```

Figure 13: Laser-sensor Arduino coding

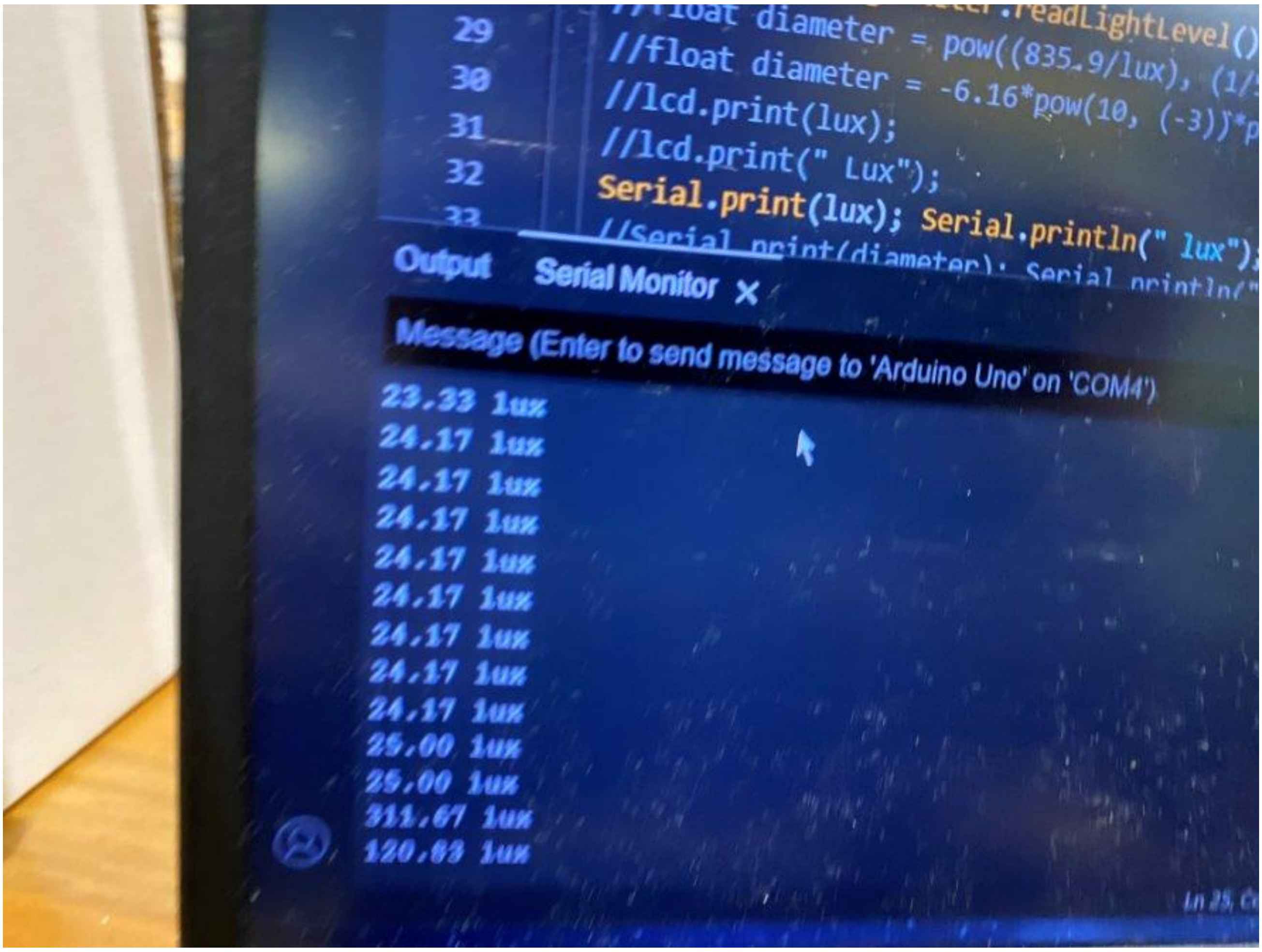

Figure 14: Lux Output Measurement

Experiment 2: Consistent Accurate Readings for Different Diameters

To evaluate the consistency and accuracy of light measurements from a laser as it interacts with filament of varying diameters. The experiment used the same type of material PLA but with two specific diameters: 1.75mm and 2.88mm. These filaments are premade so there will be no filament error when testing. These filaments will be guided slowly through the system, a method designed to ensure precision in capturing data. This controlled pace allows for the accurate assessment of how different filament thicknesses affect the transmission of laser light. Furthermore, we can use these data to convert the lux measurement to millimetres for the filament diameters which will be used for the freshly made filament.

Experiment 2 Apparatus:

- 60cm of different diameters filament, PLA (1.75 & 2.88)
- Laser pointer
- Light Sensitivity Sensor

Experiment 2 Method:

1. Arrange the experimental setup as illustrated in Figure 12. Ensure all components are correctly positioned and securely mounted.
2. Set up the code as shown in Figure 13. Ensure that all parameters are accurately inputted, and that the library is fully UpToDate.
3. Gently pull the premade filament through the designated opening in the setup, ensuring the laser directly hits the filament. This alignment is crucial for accurate data capture.
4. Record the data as the filament interacts with the laser. Ensure that the data acquisition system is properly calibrated and running smoothly to capture accurate readings.
5. Repeat steps 2 and 3 for each diameter of filament.

Experiment 2 Results:

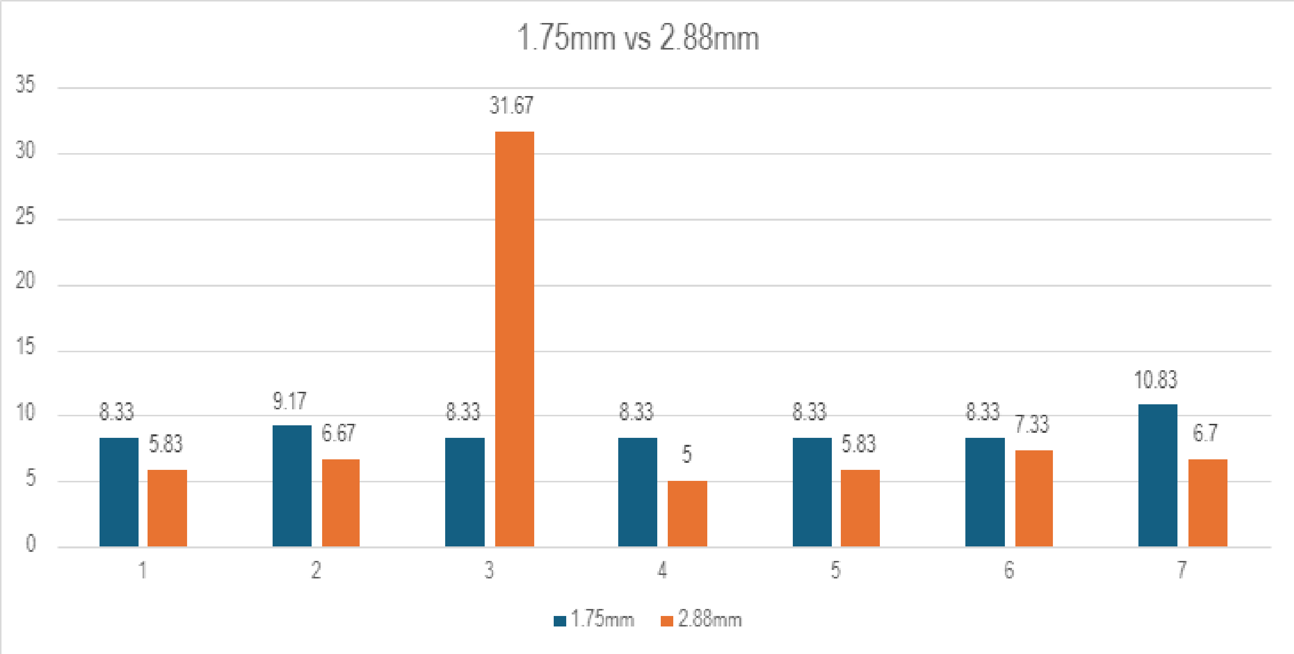

Figure 15. Results of experiment 2

When conducting tests on PLA filaments with different diameters, it is seen that the filament thickness significantly influences the light intensity measurements. As when looking at the graph we can see the 1.75mm filament diameters shown an average lux of around 8.33 lux while the 2.88mm filament produce a lower measurement of 5.83 lux. This decrease in lux measurement shown how the thickness of the diameters block light from passing through and making the sensor from picking up the full measurement. Therefore, based on these data we can convert this measurement from lux to millimetres. However, we were unable to make the equation work for the filament as there were too much mix data when materials are place through which create an incorrect reading which make the equation become ineffective.

Note: In the graph, there is a sudden increase in the reading which is due to the filament having deformed or eaten through which cause it to misshape and creating these errors. (figure 15)

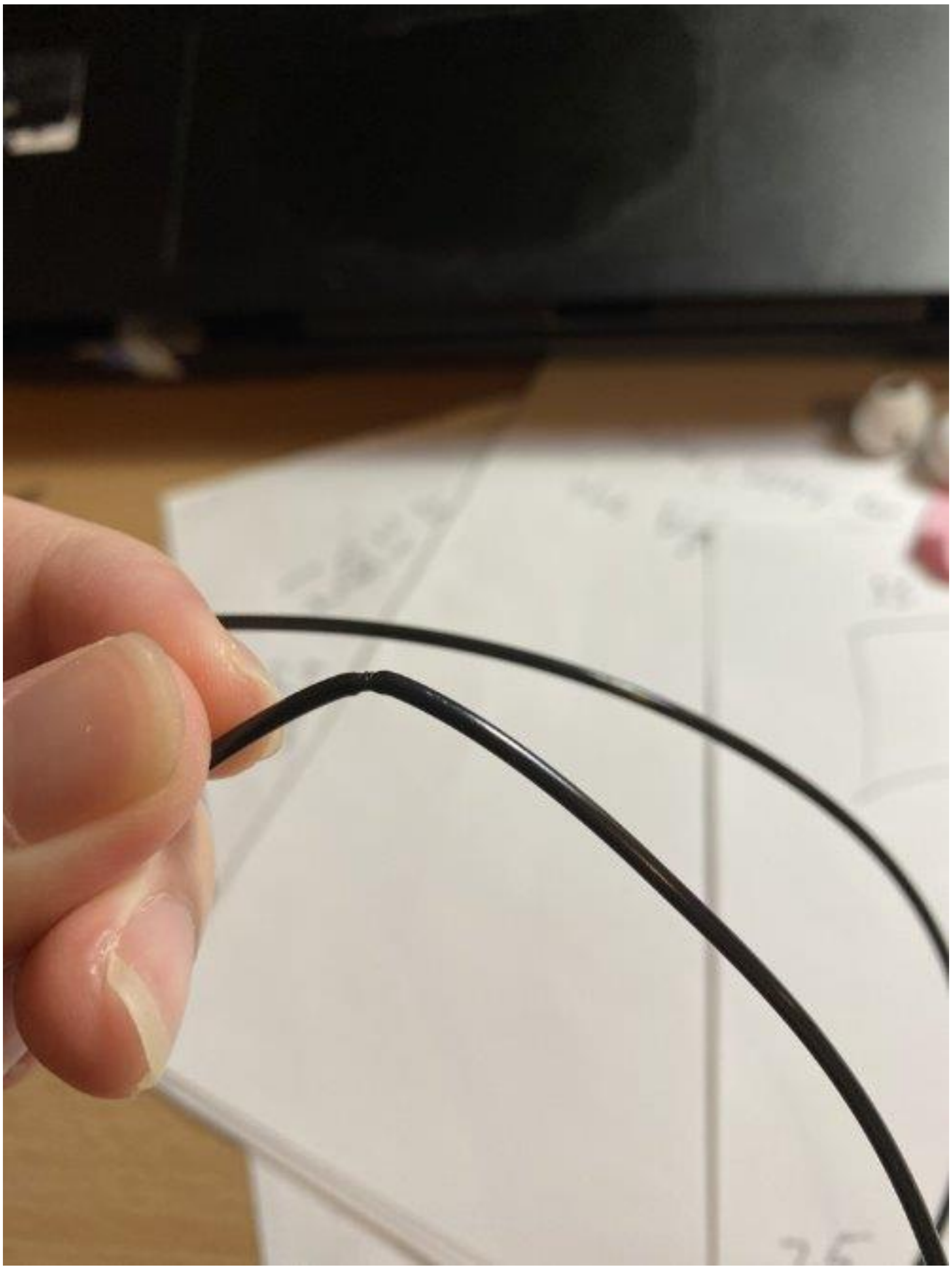

Figure 16: Deformed filament, not good for testing.

Experiment 3: Consistent Accurate Readings with Different Positioning

To determine the consistency and accuracy of the light measurement when changing the filament's position in relation to the laser and the sensor will impact the stability of the measurement reading. In the setup, the filament will be positioned to move either in the middle or close to either the laser or the sensor to determine at which location does it produce the most accurate reading. Furthermore, we can use this data to redesign the system to get the most accurate reading.

Experiment 3 Apparatus:

- 60cm of PLA filament
- Laser pointer
- Light Sensitivity Sensor

Experiment 3 Method:

1. Arrange the experimental setup as illustrated in Figure 12. Ensure all components are correctly positioned and securely mounted.
2. Set up the code as shown in Figure 13. Ensure that all parameters are accurately inputted, and that the library is fully UpToDate.
3. Gently pull the premade filament through the designated opening in the setup, ensuring the laser directly hits the filament. This alignment is crucial for accurate data capture.
4. Record the data as the filament interacts with the laser. Ensure that the data acquisition system is properly calibrated and running smoothly to capture accurate readings.
4. Repeat steps 2 and 3 for each position of filament.

Experiment 3 Results:

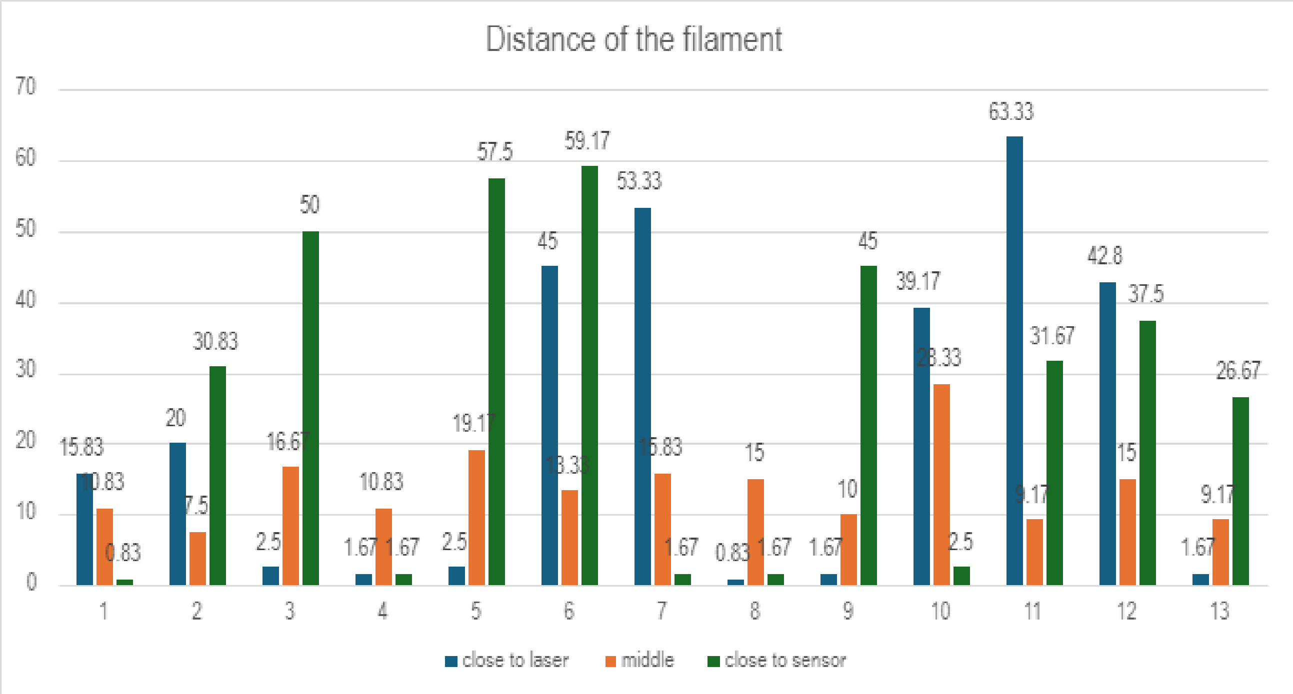

Figure 17. Shows the results of experiment 3

In assessing the optimal positioning of filament relative to their interaction with the sensor, three distinct locations were tested: close to the sensor, close to the laser, and in the middle between both. Base on the data taken, its shown that the position closer to the laser and the middle seem to produce the most sustainable reading while closer to the sensor produce a unstable reading. This is due to the light reflecting on the filament which depending on the position will create different result. Therefore, if it's close to the sensor it will block the light which make the result become in accurate. So, based on this result, we have setup the filament to be close to the laser for more accurate reading.

Tensioning System

Unless stated otherwise:

- Left heating: 150*C
- Middle heating: 140*C
- Right heating: 50*C
- Extrusion rate = 410 gauge

Experiment 1: Is the Pulling Action of the Motor Sufficient for Tensioning?

To test whether the pulling action of the rollers is sufficient, freshly extruded but cooled filament (mystery 1588ATL) will be placed inside of the rollers. Filament in the tensioner should be relatively difficult to pull out when tugged but also remain in its circular shape previous to the tensioning. This is a qualitative experiment.

Experiment 1 Apparatus:

- Desktop SJ35 extruder
- Cooling and Tensioning assemblies
- 300g of dried ABS plastic pellets
- Metal spatula
- Pliers

Experiment 1 Method:

An experimental setup can be seen in figure 21.

1) Heat the extruding device to temperatures suitable for the extrusion of ABS plastic.
2) Once heated, run the system to extrude material from previous uses, use a high speed setting (e.g., >800 gauge (8.7 RPM)).
3) After previous material has been removed from the system, place about 150-300g of ABS plastic pellets into the hopper.
4) Run the system again on a high setting *until* the filament extruded is consistent – this step is to remove any other residue not previous vacated, have a metal spatula ready to catch freshly extruded material should it misguide itself or splatter.
5) Turn on the cooling and tensioning assemblies.
6) Extrude the material using a speed of 2.97 RPM (220 gauge) and use pliers to pass it through the cooling system. Should the microstepping mode change or you wish to use a different gauge setting, refer to the Excel sheet "Stepper motor calculations for code" as can be pictured in figure 22.
7) Parse the filament through the rollers of the tensioning device, this will be running at a speed of 4 RPM (myStepper.setSpeed(400) using full microstepping).
8) Wait until filament diameter stabilises, IF:

   a. The filament breaks, lower the tensioning speed (e.g., to 2.5 RPM (myStepper.setSpeed(250))).
   b. The filament is too large or tangles, increase the tensioning speed (to 6 RPM (myStepper.setSpeed(600))).

9) Once diameter has stabilised, observe action of the rollers and filament passing and record observation.

Experiment 1 Results:

Here, figure 18. shows a control sample (bottom) and an increased tensioning sample (top) of material extruded. It can be observed that the filament with increased speed applied to the tensioner is of a smaller diameter. Figure 19. demonstrates this thinning effect displaying the test length decreasing as speed of the tensioner increases with smaller a diameter of the inside spiral length representing increased speed. When the speed of the tensioner was reduced however the filament began to significantly deform and curve (see fig. 20). This is explainable as filament is being extruded quicker than it can be pull, resulting in slack.

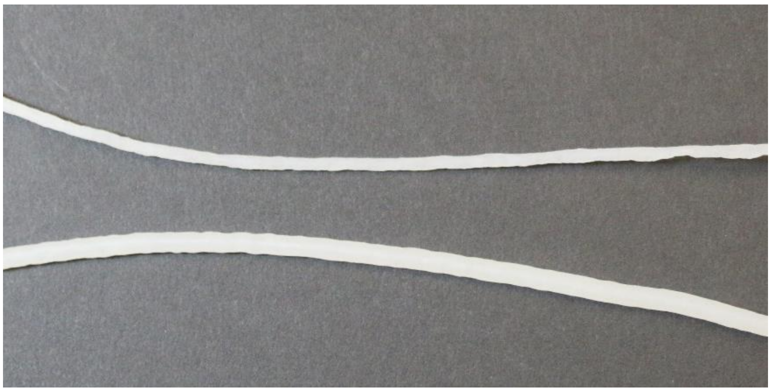

Figure 18.

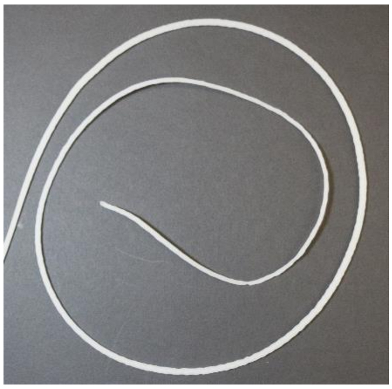

Figure 19.

An unexpected result from this experiment were undesirable geometric artefacts. As can be seen in Figure 18 and 20., the filament extruded has an uneven surface of pattern-like sharp increases and decreases of diameter. The suspect for this is the physical action of the stepper motor actuating steps using the full microstepping mode. In this case, a full microstepping mode would mean that each angular step is relatively large (1.8°), resulting in noticeable vibration and jagged motion of the drive shaft. As such, a smaller microstepping mode which would divide these large angular steps into smaller increments, should in theory allow for smoother motion and reduced vibration. This was later verified in Experiment 2 which used a 1/16 microstepping mode with noticeable improvements in filament consistency (see fig. 23.)

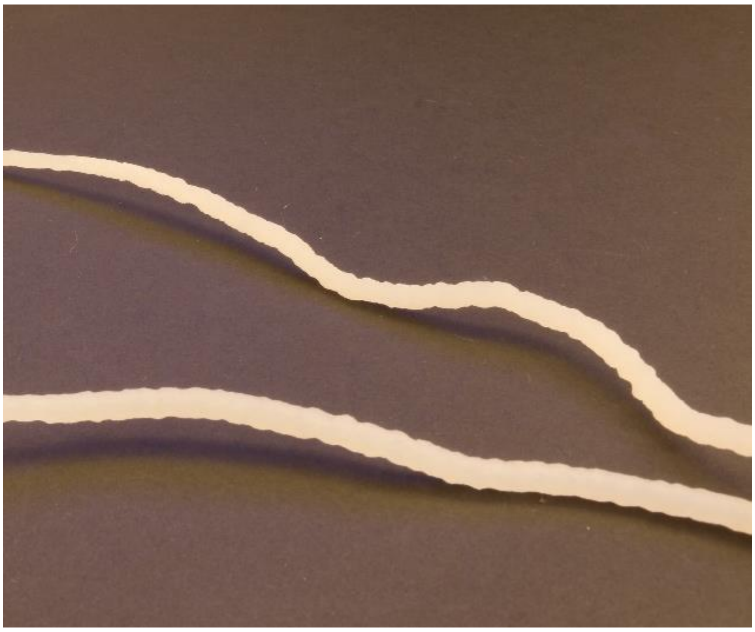

Figure 20.

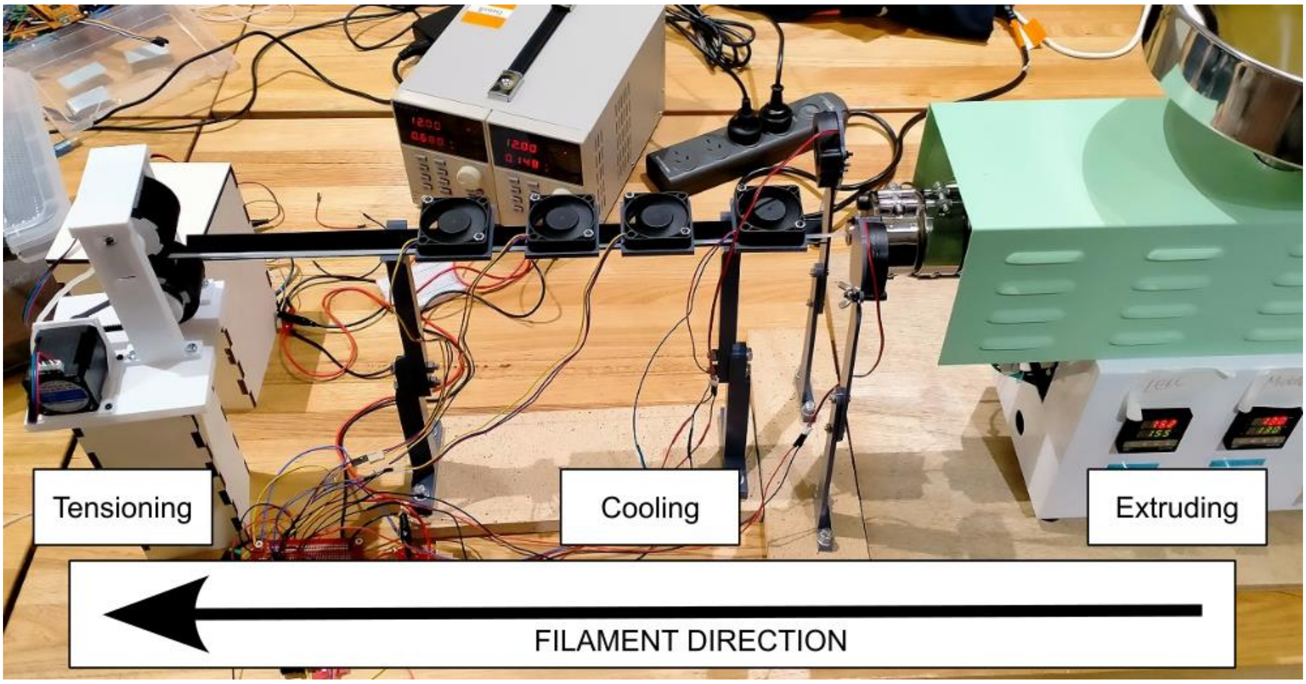

Figure 21. Shows the experimental set up of tensioning experiments 1 and 2. From right to left displays the extruder, the cooling assembly, and tensioning assembly.

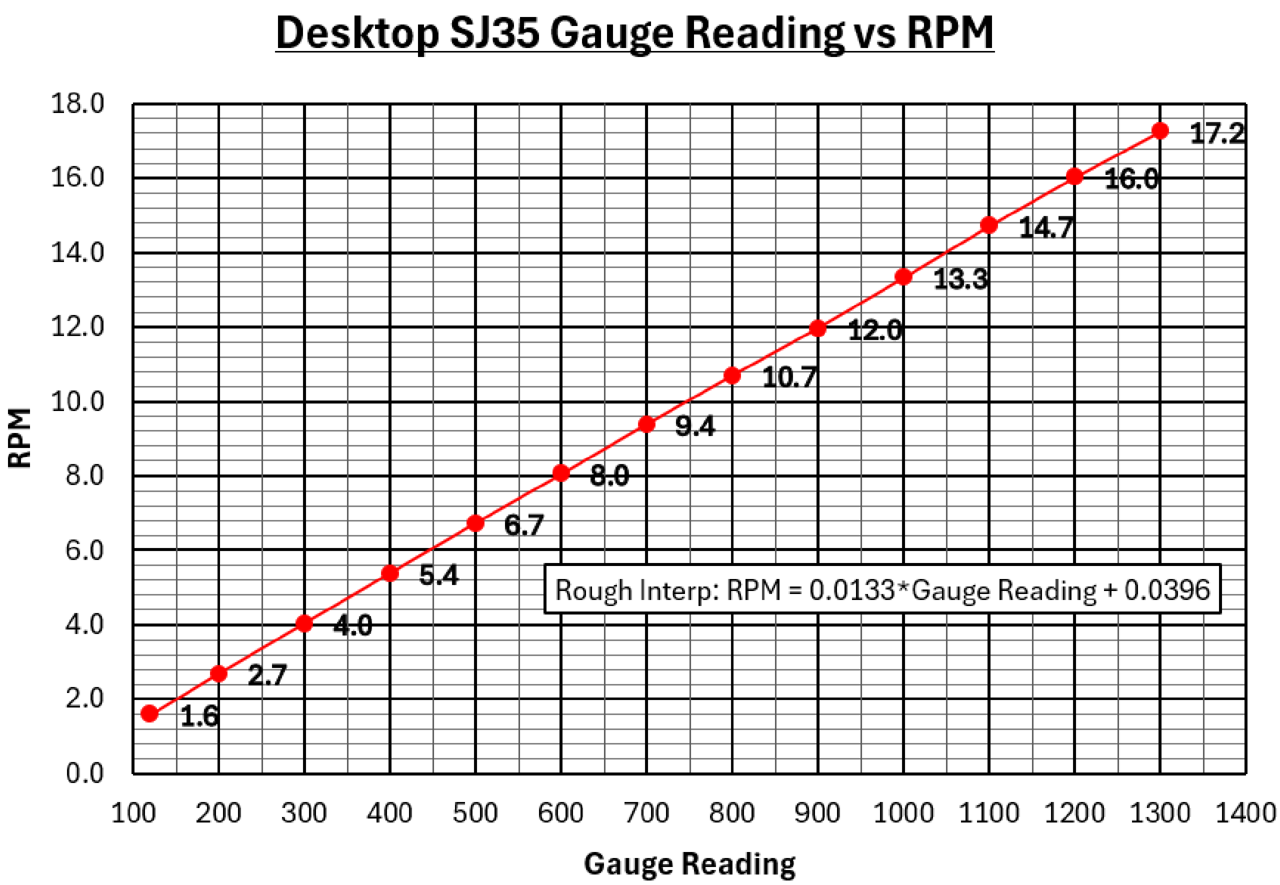

Figure 22. Shows the relationship between the extruder's gauge reading to the actual RPM values produced. A linear pattern is observed.

Experiment 2: Verify the relationship between stepper speed and filament diameter

To test how increasing or decreasing the speed of the pulling action of the tensioner will affect the geometric properties of extruded filament (i.e., diameter). Here, the stepper motor will have its speed adjusted to three preset settings: a slow speed (filament pulls through slower than is being extruded), a medium speed (filament pulls through at a similar rate to its extrusion rate), and a fast speed (filament pulls through at a faster speed than is being extruded). Afterwards, a visual inspection along with measurement of diameter will be conducted to determine the effect of the speed change. This is a qualitative and quantitative experiment.

Experiment 2 Apparatus:

- Desktop SJ35 extruder
- Cooling and Tensioning assemblies
- 300g of dried ABS plastic pellets
- Metal spatula
- Pliers
- Magnifying device
- Vernier calliper

Experiment 2 Method:

1) Heat extruding device to temperatures suitable for the extrusion of ABS plastic.
2) Once heated, run the system to extrude material from previous uses, use a high speed (>800 gauge (8.7 RPM)) setting.
3) After previous material has been removed from the system, place about 150-300g of ABS plastic pellets into the hopper.
4) Run the system again on a high setting until filament extruded is consistent – this step is to remove any other residue not previous vacated, have a metal spatula ready to catch material.
5) Turn on cooling and tensioning assemblies.
6) Extrude material (at RPM = 5.5) and parse through cooling system using pliers or a similar device.
7) Parse the filament through the rollers of the tensioning device (using the Arduino code provided in Appendix X.)
8) Wait until filament diameter stabilises, IF:
    a. The filament breaks, lower the tensioning speed.
    b. The filament is too large or tangles, increase the tensioning speed.
9) Once a “Goldilocks zone” extruding speed is achieved, alter the Arduino code controlling the tensioning speed to increase to the following values:
    - RPM = 5.5, 6, 7, 8, 9, 10, 15, 20, 30, 35, 40, 70

10) After at least 1 pass through the extruding and tensioning systems for a particular RPM value has been completed, use a vernier calliper to take measurements of the filament diameters and record this data.

Experiment 2 Results:

Samples collected from the experiment which were measured can be viewed in figure X. It shows relatively consistent filament reducing in diameter as the RPM value of the tensioning system is increased. Raw data of these measurements can be seen in Table 1. which was used to plot an RPM vs Diameter relationship (see Figure 24.). It should be noted that at 70 RPM, filament geometry became unstable and unpredictable, this was reflected in the wide spread of measurements documented. Thus, for future testing a limit should be found in maximum RPM values permissible for a particular filament at a certain extrusion rate.

This experiment also tested the effect of reducing microstepping mode to 1/16th, this resulted in an improved surface finish to the extruded filament (see Fig 23.) as compared to Experiment 1's Full step microstepping (see Fig. 20.).

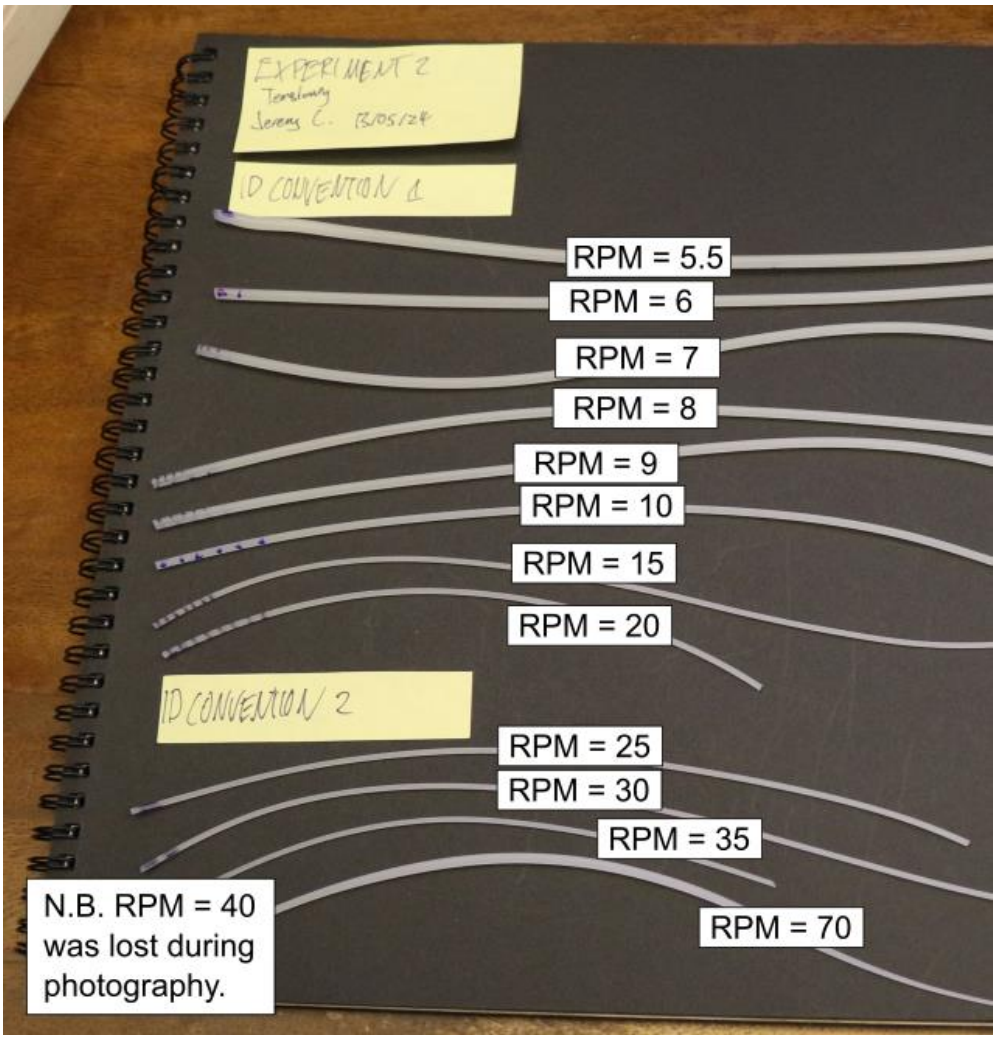

Figure 23. Shows a compiled display of the filaments and their respective RPMs.

Table 1. RPM vs Filament Diameter												
	RPM											
Measurements	**5.5**	**6**	**7**	**8**	**9**	**10**	**15**	**20**	**30**	**35**	**40**	**70**
Measurement 1	3.81	3.31	3.36	3.15	2.81	2.18	1.56	1.45	1.48	1.42	1.26	1.73
Measurement 2	3.84	3.24	3.34	3.19	2.81	2.18	1.56	1.43	1.52	1.42	1.26	2.13
Measurement 3	3.76	3.28	3.04	2.77	2.84	2.15	1.55	1.47	1.51	1.49	1.33	2.65
Measurement 4	3.76	3.23	3.01	2.83	2.88	2.19	1.58	1.52	1.49	1.39	1.33	2.55
Measurement 5	3.81	3.25	3.04	2.84	2.87	2.14	1.51	1.46	1.52	1.37	1.33	2.21
Measurement 6	3.74	3.26	2.99	2.85	2.94	2.18	1.54	1.48	1.52	1.38	1.30	1.65
Measurement 7	3.75	3.26	3.04	2.88	3.00	2.16	1.52	1.45	1.48	1.42	1.31	0.61
Measurement 8	3.74	3.20	3.04	2.80	2.89	2.15	1.54	1.45	1.52	1.40	1.29	0.88
Measurement 9	3.80	3.26	3.00	2.80	2.71	2.14	1.53	1.47	1.50	1.43	1.32	1.33
Measurement 10	3.83	3.29	3.02	2.80	2.66	2.13	1.50	1.42	1.49	1.43	1.27	1.41
Average	3.78	3.26	3.09	2.93	2.84	2.16	1.54	1.46	1.50	1.42	1.30	1.72

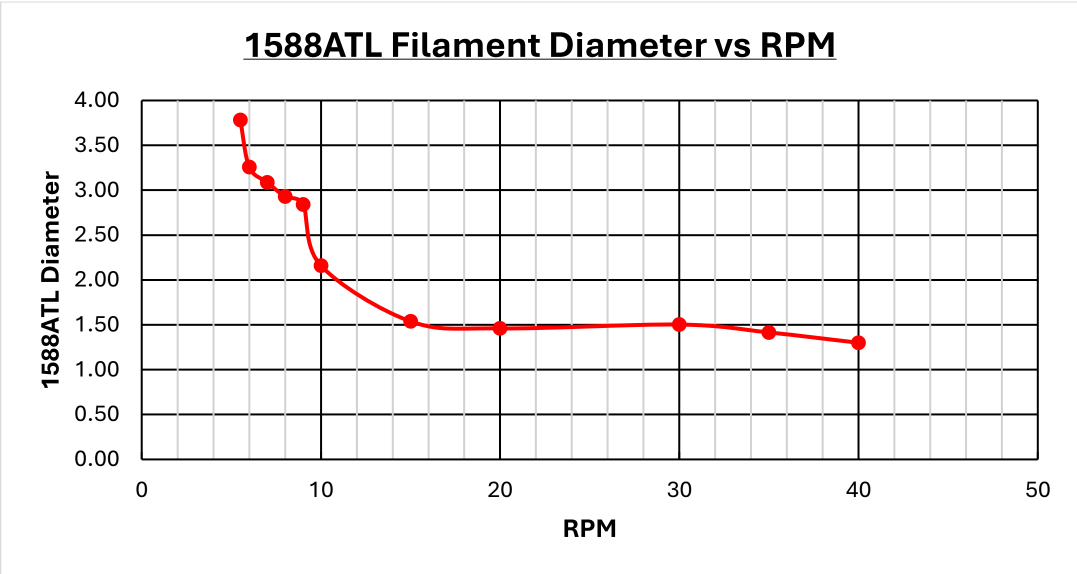

Figure 24. Graphed results of filament diameter vs RPM.

```
// N.B. THE STEPPER MOTORS SHOULD BE SET TO FULL MICROSTEPPING MODE: 1, 1, 1
#include <Stepper.h>
#define BASESPEED 33600 // 33600 = roller RPM of 7, refer to the "Stepper Motor Calculations for Code.xlsx" sheet
#define STEP 28800 // 1 full revolution for the specific roller diameter and its speed ratio
Stepper myStepper(6, 5, 4); // Arduino pin allocations for the stepper motor driver

void setup()
{
  pinMode(6, OUTPUT); //Enable
  pinMode(5, OUTPUT); //Step
  pinMode(4, OUTPUT); //Direction
  digitalWrite(6, LOW); //Stepper is On? LOW = Yes, HIGH = Off
}

void loop(){

  myStepper.setSpeed(BASESPEED); // speed of stepper motor
  myStepper.step(STEP); // steps of the stepper motor (refer to Excel sheet,
                        //n.b. DO NOT exceed above 1 revolution per step)
// IF YOU WANT TO TEST MOTOR PERFORMANCE BY PERFORMING 2 REVOLUTIONS
  // myStepper.step(STEP); // Repeated myStepper.Steps to program the stepper to move more than one revolution
  // myStepper.step(STEP);
  // delay(1000); // delay required in order to see the stepper move particular steps, else infinite rolling
}
```

Figure 25. Example of code used in these tests. Note that the BASESPEED and STEP values will need to be adjusted for the experiment.

VARIABLES				
Pulse Ratio:		3.00		
Stride angle:		1.80		
Microstepping mode:	Full	1.0000		
RESULTS				
Actual Pulse-to-Angle ratio		0.60	deg/pulse	
Steps for a full revolution:		600.00	pulses/rev	
ARDUINO CODE HELP				
I want to:				
Perform x amount of revolutions	x:	5.00	"steps" required:	3000.00
X RPM	x:	30.00	"speed" value:	3000.00
MICROSTEPPING MODES (DO NOT TOUCH)				
Step		**MS1**	**MS2**	**MS3**
Full	1.0000	L	L	L
Half	0.5000	H	L	L
Quarter	0.2500	L	H	L
One-eighth	0.1250	H	H	L
One-sixteenth	0.0625	H	H	H

Common pulse ratios to achieve the specified "Stride angle" for a Full step Nema 17 motors are 1:3 (e.g., 1 1.8deg movement requires 3 pulses).
In this case, type "3"

How many degrees the shaft actually rotates per pulse. A calculated value

Figure 26. Shows a preview of the used Stepper Motor Calculations for Code Excel spreadsheet.

Spooling System

Unfortunately, due to the late arrival of parts the spooling system could not be properly experimented and tested. Despite this, the system was found to work in parts.