Tungsten-Infused Filaments for Additive Manufacturing

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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1. Abstract

The benefits of a Tungsten-infused plastic filament are discussed in the context of particle detection experiments. A methodology for manufacturing custom filaments is considered, planned, and tested, utilizing a Filabot Wee filament extruder and Arduino-controlled feedback loops for quality assurance. Similar products and Tungsten-infusion techniques are reviewed, and compared with the intended manufacturing methodology. Drawbacks of and restrictions on current intended methodologies are used to select an optimal technique for Tungsten-infused filament development.

2. Introduction

2.1 Tungsten in radiation shielding

Tungsten, much like lead, is a heavy metal whose structure effectively blocks electromagnetic and particle radiation. The deceleration of charged particles upon entering tungsten causes these particles to emit highly energetic photons. For thick blocks of tungsten this radiation dissipates before exiting, but for thin sheets of tungsten a shower of radiation can be detected in scintillators on the far side of the material (Olive, et. al., 2014).

Because Tungsten lacks the health hazards associated with handling Lead, it is a popular choice in detector components for both blocking radiation and increasing the energy generated by the primary particle. Unfortunately, tungsten's hardness presents other challenges which are absent from softer lead. Tools for machining metal components are often made of tungsten carbide, and the increased wear associated with machining a block of tungsten can significantly increase production costs (Deconinck, 2015).

Current applications for tungsten and other radiation-blocking heavy metals include experimental detector parts which produce radiation showers, radiation shielding for detector electronics, and radiation masks for tumor radiation treatments at the Hampton University Proton Therapy Institute. In each case, components must be manufactured to custom specifications in single-component or small-run batches. The time and cost associated with machining solid tungsten is a significant hindrance to the production of these components (Deconinck, 2015).

2.2 Plastic composites and additive manufacturing

Additive manufacturing, a process whereby 3-dimensional objects are built by the iterative addition of material, has enjoyed a recent rise in popularity among Do-It-Yourself enthusiasts thanks to its relatively low tooling cost and high versatility. Modern 3D-printers “print” objects by melting plastic filaments and extruding them through a print nozzle, which draws each layer of the object in the xy-plane before incrementally increasing its height above the bed to print the next layer. This allows users to build objects of nearly any shape with only a single piece of equipment, and convert 3-dimensional computer models to physical objects in a matter of hours.

The ability to produce custom-built tungsten detector parts in such a fashion could drastically shorten production time and machining costs, but the temperatures and precision involved in 3D-printing metal objects makes this process prohibitively dangerous and expensive. A solution could be to combine the ease and simplicity of low-cost plastic printing techniques with the radiative properties of tungsten.

By infusing a plastic filament with tungsten grains or particles, it should be possible to produce custom parts with the necessary radiative properties without the need to machine these parts from extremely hard tungsten blocks.

2.3 Review of similar products & techniques

The proponents of a technique for 3-D printing tungsten-based radiation shielding applied for a patent in March, 2015, but to date no patent has been granted for their application. This method describes the use of “a compound comprised of at least 90-percent tungsten by weight or alternatively 40 to 60 percent tungsten by volume” (Yanke, Durkee, & Douglas, 2015). The claims of this application are an electromagnetic shielding component such as Tungsten added to a “thermoplastic polymeric material” in “particles having a diameter of greater than 2.0 and less than 100.0 microns” (Yanke, Durkee, & Douglas, 2015). The composite material is then “dispensed from the three dimensional printing tool in a thread having a diameter between 0.30 and 0.60 millimeters (Yanke, Durkee, & Douglas, 2015). While this process has not yet been approved for a patent, it may serve as a set of useful guidelines in the development of our own tungsten-infused filament.

Tungsten-infused filaments are also commercially available from makergeeks.com, but only in 1.75mm thicknesses which are incompatible with our printer (Maker Geeks.com, 2015). While it may be possible to melt this filament down and re-extrude it, it typically retails at $195.95 for a half-kilogram spool, though the current discounted price is $79.95 per half-kilogram. When compared to $6.31 per pound for ABS pellets (Filabot, 2015a) and crystalline tungsten powder priced at $35.00 per pound (Buffalo Tungsten Inc., 2015), a 90%-tungsten composite will cost only

$32.13. These prices make the purchase of pre-made tungsten-infused filament a fiscally irresponsible decision in the long run.

Other methods for tungsten composite production include mixing heavy metals into epoxy resin (Hu, et al., 2014), coating tungsten powder with a “coupling agent” before mixing in plastics and “kneading” until an even consistency is reached (Zhou, et al., 2012). This latter method could possibly be an effective way to pre-mix a composite before extruding, but the former epoxy-based method would require custom molds to be created and is thus not a form of additive manufacturing. It is possible, however, that epoxies with a higher Tungsten content by volume could be used to fill a hollow 3D-printed structure, and thus should not be ruled out for future research.

3. Experimental Design

3.1 Filabot Wee

Because pre-made filaments are often more expensive than bulk plastic, the production of homemade filaments can provide significant economies of scale. For this reason, the Filabot Wee is a consumer-grade plastic extruder designed for creating 3D-printer filaments from ~5mm pellets. A temperature controller allows users to set custom extrusion temperatures, and enables extrusion of common 3D-printing materials such as ABS, PLA, Nylon, and more. The apparatus, diagrammed in Figure 3.1.1, consists of a hopper, an extruder screw driven by an electric motor, and a heating element.

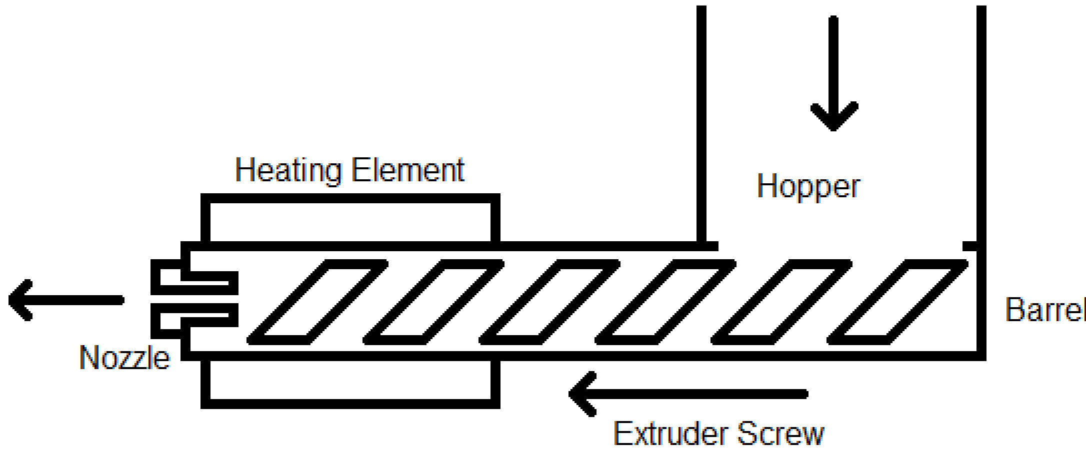

Figure 3.1.1 Filabot Wee Extruder Diagram

Plastic pellets in the hopper fall into the grooves in the extruder screw and are forced along the extruder barrel. The heating element then heats the pellets into molten plastic before the extruder screw forces them out of the extruder nozzle. This relatively simple process is often coupled with a spooling mechanism to make the resulting filament consistent and easy to transport. Without a spooling mechanism, the resulting filaments are “drop-spooled”, or allowed to hang freely to the floor. This process is depicted in Figure 3.1.2. Once the length of the filament grows beyond the distance to the floor, tension on the extruded filament can become inconsistent depending on handling methods.

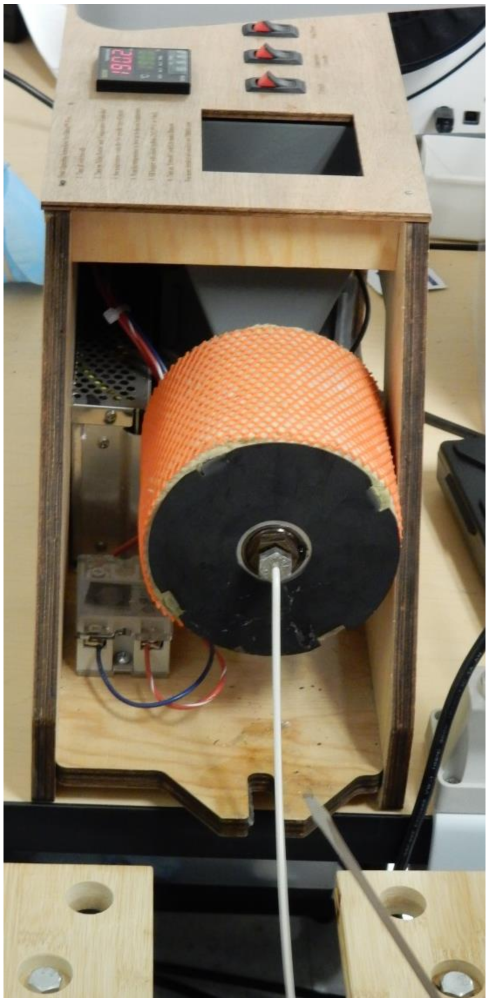

Figure 3.1.2 Drop-Spooling illustration, where ABS filament hangs from the extruder nozzle.

3.2 Factors in filament manufacturing

In producing a consistent filament, several factors need to be monitored and controlled to a reasonable precision. Conditions in the extrusion process must produce a filament which is (i) of a printable thickness, (ii) capable of printing a structurally sound object, and (iii) in possession of the necessary non-structural qualities for the application (e.g. improved radiation thickness for tungsten-infused filaments).

The major factors which affect filament thickness are expected to be filament tension and extrusion temperature. High temperature filaments have lower viscosity, causing them to stretch and thin due to tensile forces. In filaments with poor material consistency this stretching can lead to disproportionate thinning, or necking, in certain lengths of the filament.

The integrity of the molecular structure of the filament will be decided by the shape and consistency of its constituent molecules, airborne contaminants and humidity, extrusion speed, and filament cooling rates. Each of these factors contributes to the final orientation of the molecules as they cool, but may be somewhat less relevant to the structural integrity of the final product than the conditions in which the filament is printed.

3.3 Extruder Design

In light of these considerations, an apparatus has been designed which will improve the Filabot Wee extruder by adding Arduino-controlled feedback loops to adjust the associated parameters. This apparatus is diagrammed in Figure 3.3.1.

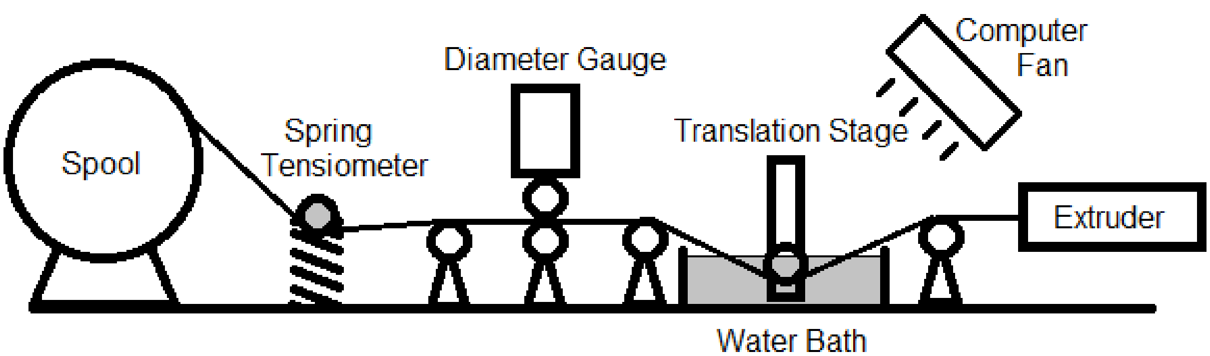

Figure 3.3.1 Annotated Extruder Apparatus Diagram

The apparatus begins with a Filabot Wee which has been modified to accept either user inputs from the local controls mounted to its top panel or automated inputs from an Arduino. Filament is extruded onto a track of wheels with a V-shaped cross-section (V-wheels) which guide the filament through the apparatus. As it travels, the filament is cooled by a variable-speed computer fan whose inputs are also controlled by the Arduino.

A translational stage is used to control the path of the filament through an optional water bath. Time spent in the bath is a function of the path length, which is again controllable with the translational stage, while the temperature of the bath is monitored by the Arduino through an underwater temperature sensor. Initially, water temperature will be manually controlled, but future improvements of the apparatus could include a resistive heating element to regulate the bath temperature.

The thickness of the filament is then measured by a thickness gauge attached to two wheels, and this measurement is returned to the Arduino controller. Tension is provided by an electric motor on the spooling mechanism and measured by the position of a spring attached to the filament by a v-wheel. Greater spring extension indicates higher tension on the filament, and the Arduino will vary the speed of the motor to maintain constant extension of the spring. The spooling mechanism will also move horizontally along its axis of rotation in a periodic fashion such that orderly layering of the filament on the spool is maintained. The exact methods for obtaining this additional degree of freedom have not been fully prescribed.

Inspiration for a majority of this apparatus was derived from a Russian-language Youtube video by Sergey Efremov (2015). Programming for all feedback loops in this apparatus will be determined empirically by varying each setting independently to determine optimal print conditions for each material.

3.4 Tungsten Extrusion considerations

The first major concern for a tungsten composite filament is developing a uniform consistency throughout the filament. This requires perfect mixing of the plastic, in this case ~5mm ABS pellets, and micron-scale tungsten powder not only in the hopper of the extruder but throughout the extrusion process. A lower limit of particle size for loose Tungsten powder is set first by breathing hazards, and second by manufacturing tolerances in the extruder. If particles are smaller than the gap between the wall of the extruder and the extruder screw, the apparatus may not effectively extrude these particles. An upper limit of particle size is cited by Maker Geeks.com as the size of the intended print nozzle, as 0.4mm print nozzles “have a higher likelihood of clogging” with their tungsten filament (2015), but it may be wise to stay well below that limit to improve material consistency.

Another major consideration is the hardness of Tungsten which, according to the Maker Geeks.com instructions for printing tungsten-infused filaments, will destroy a print nozzle within a few hours of printing (2015). As a result, all parts of the extruder mechanism which may grind against or otherwise come in contact with the tungsten powder must be regularly checked for premature wear.

A third concern is a difference in the thermal conductivity of the plastic and the Tungsten that may result in different cooling rates. It is possible that drastic differences between the two materials could cause fracturing in the filament if it were cooled too quickly.

3.5 Modifications to general extrusion procedure for the production of tungsten-infused filaments

To create the tungsten-infused filament, two methods for pre-mixing the Tungsten and plastic are considered. The first is mixing through a metered hopper system which releases tungsten powder and plastic into the extruder at measured rates. This method, while simple, cannot guarantee a consistent mixture of materials over the length of the filament as a result of different particle sizes behaving differently in the extruder screw mechanism.

The second method is to coat the plastic pellets in tungsten powder before placing them in the Filabot hopper. This coating is accomplished by heating the plastic pellets until their surface is adhesive and mixing them with Tungsten powder. Composition will be characterized by weighing the plastic pellets before and after the coating to measure the ratio of the two materials by mass. This method is more likely to improve consistency over the length of the filament, but may also cause premature wear on the Filabot extruder.

Once the first filament is produced, other procedures will be optimized to reflect the considerations mentioned in the previous section.

4. Preliminary Results

Experimental testing on this project was initially focused on developing a working understanding of the fundamentals of filament extrusion. This was been accomplished through the production of 17 ABS filaments totaling more than 93 feet in length and ten PLA filaments totaling more than 25 feet. These filaments showed a strong dependence on temperature, as depicted in Figure 4.1. These results suggest that filament diameter decreases with increased printing temperature. This can be intuited in that higher temperature plastics are softer, and thus may stretch and thin more due to any tensile force.

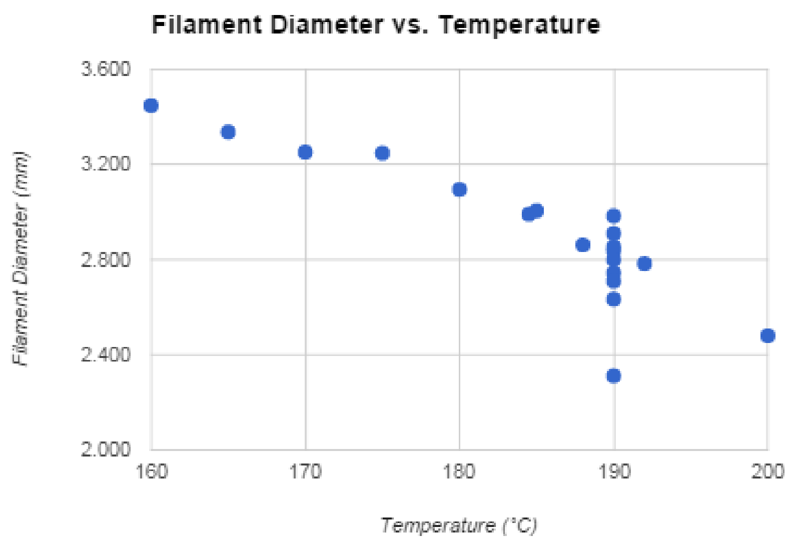

Figure 4.1 Graph of Average ABS Filament Diameter versus Extrusion Temperature.

When temperature testing was repeated with PLA filaments, it was found that temperatures above 170˚C could not produce a viable filament. Extremely high-temperature extrusions were found to lose their viscosity and could not support their own weight. While temperature dependence results were not as clear as in ABS, it was also clear from qualitative analysis that PLA filaments were not as consistent as the ABS. Filaments at lower temperatures were often wrapped onto themselves rather than drawn straight. This was evidence that an appropriate printing temperature lies somewhere between these low-temperature tests and the 170˚C maximum. A graph of PLA filament diameter versus temperature is displayed in Figure 4.2.

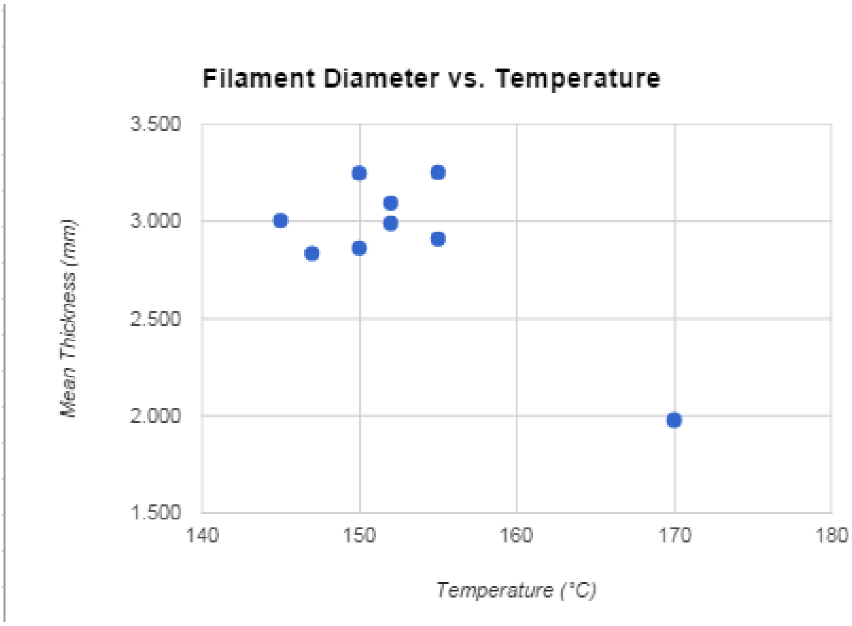

Figure 4.2 Graph of Average PLA Filament Diameter versus Extrusion Temperature.

To get a better idea of the consistency of our extruded filaments, a series of nine ABS filaments were printed at 190˚C. Data for these filaments is displayed in Table 4.1 below where D is the filament diameter. Table 4.2 summarizes these results.

Table 4.1 ABS Filaments at 190˚C

Filament	Temp (+/- 1C)	Length (in)	Mean D (mm)	σ_D (mm)
7	190	36	2.910	0.249
9	190	30	2.835	0.169
12a	190	62.5	2.744	0.130
13	190	56.5	2.983	0.150
14	190	73	2.799	0.173
15	190	98.9	2.854	0.178
16	190	142	2.633	0.358
17	190	330	2.709	0.375
18	190	429	2.311	0.336

Table 4.2 ABS @ 190˚C Summary

	Mean D (mm)	σ_D (mm)
Average	2.753	0.235
Standard Deviation	0.196	0.097

Mean diameter for these filaments is below the nominal 2.88 mm target (a requirement for our chosen 3D-printer). Figure 4.1 suggests that this result would be cause to reduce extrusion temperature to obtain the proper diameter. Our average standard deviation of the mean is also larger than our tolerances, which supports the argument that a full extruder apparatus must be built to produce consistent filaments, even at the same temperature.

Another qualitative result was that thickness of the filament decreased as it was extruded. Because these filaments were “drop-spooled,” or allowed to hang from the extruder to the floor, the tension on the filament being extruded increased as the already-extruded filament hung. Unfortunately, this qualitative analysis that tension made the filaments thinner is difficult to quantify due to inconsistencies in length and other spooling conditions. This supports our assessment that our final apparatus must be able to measure and apply consistent tension to the filament for quality assurance.

5. Improvements to the Apparatus

Eliminating excessive variation in filament diameter first required a consistently defined filament path. V-wheels were mounted to robotics-grade C-channel to provide an adjustable path between extruder and spool. To provide real-time measurements of filament diameter, a Filameasure V2 was clamped in a piece of C-channel for stability and mounted along the filament path. Below is a photo of the first prototype mounted to plywood sheeting, with a previously printed filament displaying the path.

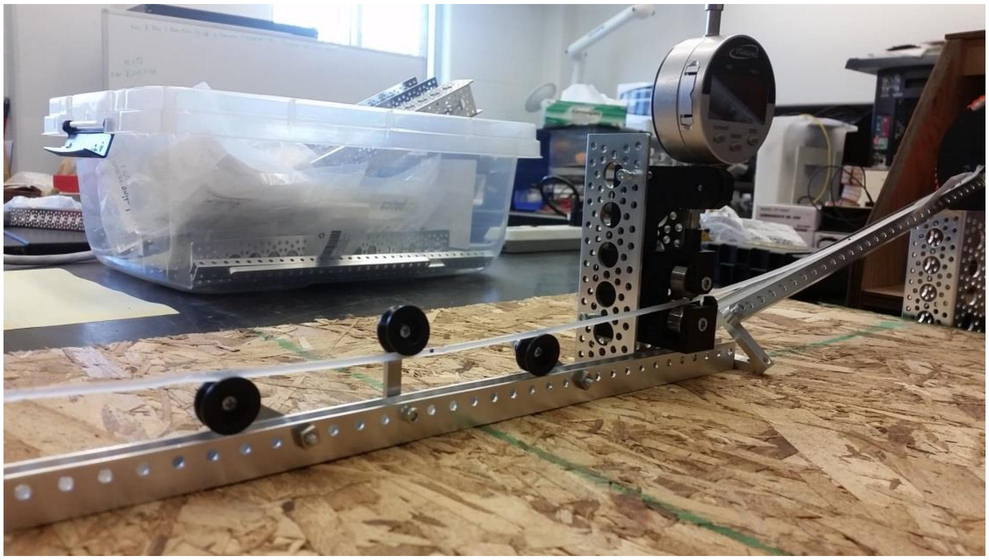

Figure 5.1 Initial prototype with Filameasure V2 and V-wheels mounted to plywood.

This initial prototype was scrapped for several reasons. Hot filaments often stuck to the metal ramp, and filament entering the gauge at an angle from the ramp would produce an artificially large diameter measurement. Future versions eliminated the ramp by mounting the apparatus to a section of 80/20 beam which raised the platform to the level of the extruder nozzle while increasing stability and modularity.

To hold the filament, a spool mount was built from two vertical lengths of C-channel. Two Actobotics set-screw hubs horizontally mount a ¼"-diameter shaft to each length of C-channel. Flanged bearings with ¼" inner diameter slide over these shafts to provide rotational freedom to two circular Actobotics mounting plates with holes to attach gears or drive pulleys. A 2.5"-long wooden dowel was cut to length to support the spool between the two circular metal mounts. A lathe was used to center a ¼" hole through the dowel, then the metal discs were mounted using the ¼" shaft as a centering tool to eliminate eccentricities and ensure rotational stability. The ¼" hole was later expanded to prevent interference between the dowel and the mounting shaft. The resulting spool mount is shown with and without a spool in Figure 5.2a and 5.2b respectively.

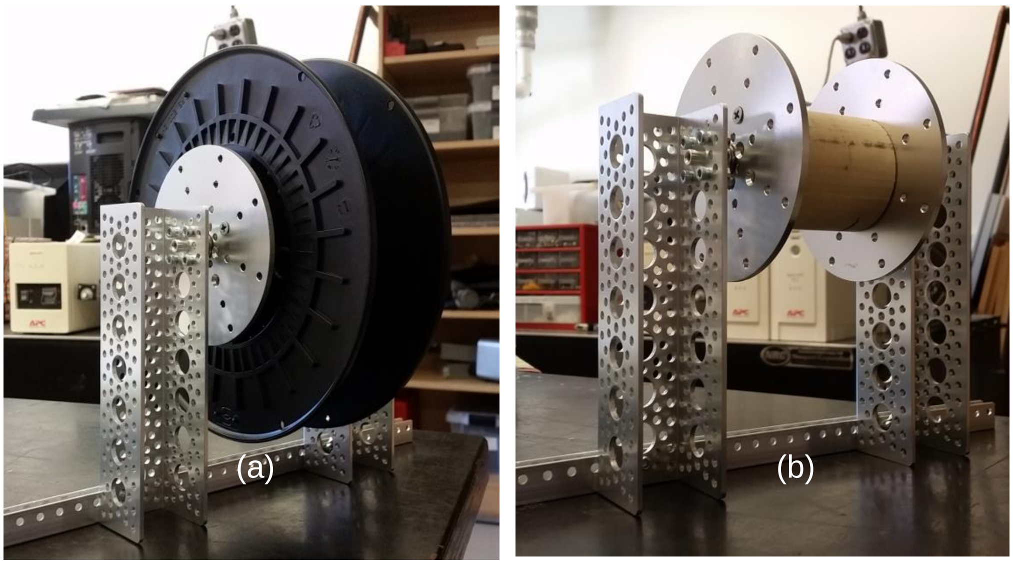

Figure 5.2 Spooler mount on robotics bearings with (a) and without (b) a spool.

A shallow plastic basin was used as a water bath for filaments such as PHA. While this basin is typically filled with water around 10˚C, ice baths and warm water baths are both achievable and the temperature is measured with a digital thermometer. Since ABS filaments cooled quickly enough in air, neither the computer fans nor the water bath were needed.

Our initial plans to drive the spooler with an Arduino-controlled motor were complicated by the limited current. An Arduino control circuit was built from the Motorized Pinwheel schematic in the Arduino Starter Kit Projects Book to power a small motor with a 9V battery (Fitzgerald & Shiloh, 2012). Unfortunately, this small motor provided very little torque and the 9V power supply was not adequate for extended filament extrusions.

Instead, a cordless DC drill motor was procured, powered by a 3.0A power supply with speed varied by voltage in the range of 0.8 – 5.0V. This larger motor provided sufficient torque and the larger power supply could easily handle extended filament extrusion sessions. A plastic v-wheel was mounted to the drive gear to enable gear reduction via belt drive.

6. Spooler Speed Tests

Determining the appropriate gear reduction required testing of both spooling speeds for actual extrusions in revolutions per minute (RPM) as well as the rotational speeds currently provided by the DC motor through a direct coupling to the spool. Knowing the spool has a circumference of 10.6cm, the direct drive configuration is useful for equating belt speed in cm/s to filament speed in cm/s, as in this configuration both are the same. Once baseline values for usable spooler RPMs and direct-drive RPMs have been established, the necessary gear reduction can be calculated to provide the appropriate filament speed given an achievable belt speed. Measured RPM for a single ABS filament spooled by hand is compared in Table 6.1 with a thickness measurement

Table 6.1 Hand-driven filament spooling RPM and Diameter measurements

Rotation	Time (s)	RPM	Diameter (mm)	Rotation	Time (s)	RPM	Diameter (mm)
1	17.97	3.34	2.95	8	22.62	2.65	3.2
2	20.36	2.95	3.15	9	21.24	2.82	3.24
3	21.09	2.84	3.18	10	19.32	3.11	3.24
4	20.82	2.88	3.16	11	21.52	2.79	3.26
5	21.61	2.78	3.22	12	21.91	2.74	3.24
6	22.02	2.72	3.18	Average	20.94	2.87	3.18
7	20.82	2.88	3.18	Std. Dev	1.27	0.19	0.08

The average speed of the spool must be approximately 2.87 RPM to produce an ABS filament, but the average speed of the belt-driven spool also needs to be measured to calculate an appropriate gear ratio. The spooler was driven in a direct-drive configuration with the motor powered by a voltage-limited power supply at intervals of 0.1V from 0.8V to 1.5V. At each voltage, the speed of the spool was recorded with a stop-watch for up to 13 revolutions. The configuration is displayed in Figure 6.1, and Table 6.2 shows resulting average time per rotation, average RPM and standard deviation of both at each voltage.

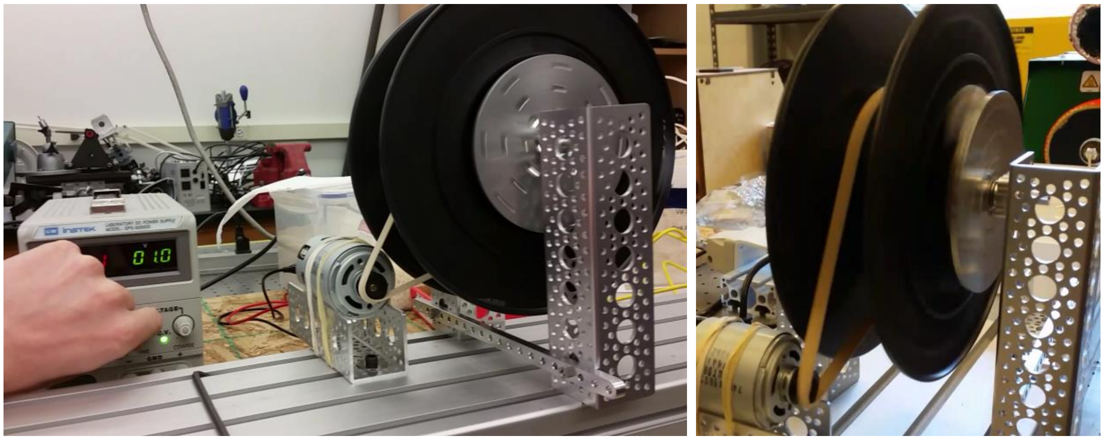

Figure 6.1 The spooler is shown driven by belt drive to equate belt speed to filament speed.

Table 6.2 Direct-drive RPM at voltages from 0.8V to 1.5V

Voltage (V)	Average Time (s)	Std Dev (s)	Average RPM	Std Dev (RPM)
0.8	1.54	0.06	38.90	1.61
0.9	0.85	0.08	70.95	7.21
1.0	0.65	0.05	92.31	7.19
1.1	0.58	0.06	102.77	11.95
1.2	0.50	0.05	121.12	11.84
1.3	0.42	0.06	142.34	20.62
1.4	0.36	0.05	168.47	21.56
1.5	0.35	0.04	169.93	19.93

The lowest RPM measured was 38.90 RPM, more than 10 times the 2.87 RPM used for spooling ABS, meaning the available belt speed greatly exceeds the necessary filament speed. To compensate for excessive belt speed v_b, a drive wheel must be attached to the spool mount with a circumference C_b to provide gear reduction X where v_f is filament speed, C_f is spool circumference, and RPM_b& RPM_h are the 0.8V belt-driven and hand-driven RPM averages respectively:

$$C_b = X * C_f = \frac{v_b}{v_f} * C_f = \frac{RPM_b * C_f}{RPM_h * C_f} * C_f = \frac{RPM_b}{RPM_h} * C_f = \frac{38.90}{2.87} * C_f = 13.58 * C_f$$

Since our RPM_b was measured at the lowest speed of the DC motor's operational range, this particular application requires a guide wheel of at least $13.58 * 10.6cm = 143.95cm$ diameter or larger. The spool mount has clearance for drive wheels with up to a 22cm diameter, and thus the maximum available gear reduction for a single gear attached to the 10.6cm-diameter spool is 2.08:1. In order to obtain a 13.58:1 ratio, it will be necessary to use an intermediate transmission wheel mounted on ½" bearings with a large input wheel and a much smaller output wheel. It is also important to note that for longer extrusions the effective spool circumference will increase as filament layers itself onto the spool, and motor speed will necessarily decrease to compensate. To accomplish this, it is best to create a transmission that allows the spool to be spun at 2.87 RPM or lower by motor speeds in the middle of the operational voltage range, allowing for better speed control and more reliable service. This transmission is diagrammed in Figure 6.2.

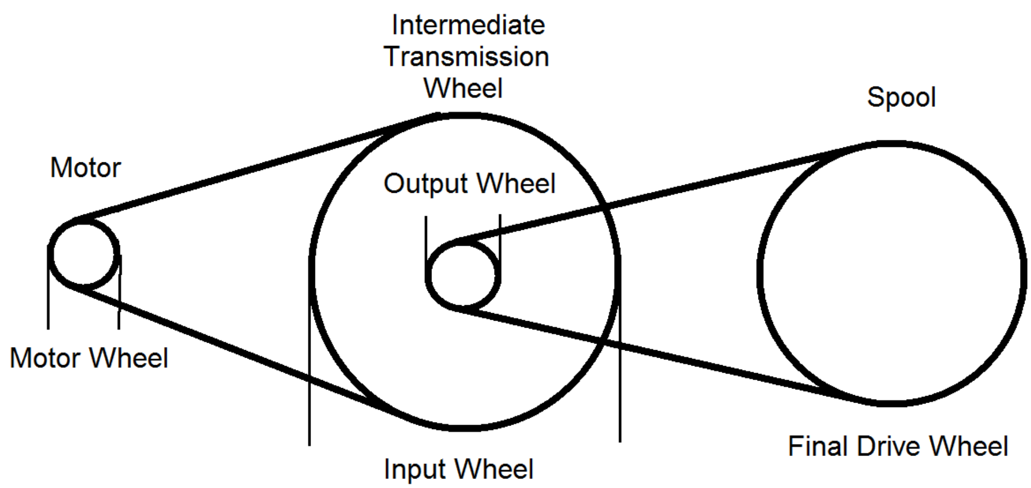

Figure 6.2 Diagram of the transmission, with motor at left and spool at right.

The Final Drive Wheel diameter was maximized to 22cm and the Output Wheel diameter was minimized to 1.92cm, restricted by the spooler mount and the ½”-bore bearings respectively. As the motor wheel’s outer diameter is set to 17.57cm, the only variable size was the Input Wheel on the intermediate transmission wheel. Selecting an Input Wheel diameter of 22.9cm provides the necessary 2.87 RPM at 0.9V. Transmission wheel dimensions are given by Table 6.3, while transmission and spool RPM calculations are given by Table 6.4.

Table 6.3 Transmission drive wheel outer and inner diameters

	O.D. (mm)	I.D. (mm)
Input Wheel	229.0	12.7
Output Wheel	19.2	12.7
Final Drive Wheel	220.0	27.0
Filament Spool	106.0	N/A
Motor Wheel	17.6	N/A

Table 6.4 RPM calculations for transmission dimensions given in Table 6.3

Voltage (V)	Direct Drive RPM	Total Reduction	Motor RPM	Transmission RPM	New Filament RPM
0.8	38.90	13.58	235	18.01	1.57
0.9	70.95	24.76	428	32.84	2.87
1	92.31	32.22	557	42.73	3.73
1.1	102.77	35.87	620	47.57	4.15
1.2	121.12	42.27	731	56.06	4.89
1.3	142.34	49.68	859	65.88	5.75
1.4	168.47	58.80	1016	77.98	6.81
1.5	169.93	59.31	1025	78.66	6.86

The Input Wheel, Output Wheel, and Final Drive Wheel can be laser-cut from a sheet of acrylic, gluing 3 circular cuts together to create a V-wheel pattern. Figure 6.3

shows the wheels being laser-cut from 3.25mm acrylic at left, with the initial wheels mocked up and drive belt routing illustrated at right. The transmission system requires the procurement of appropriately sized drive belts to be operational.

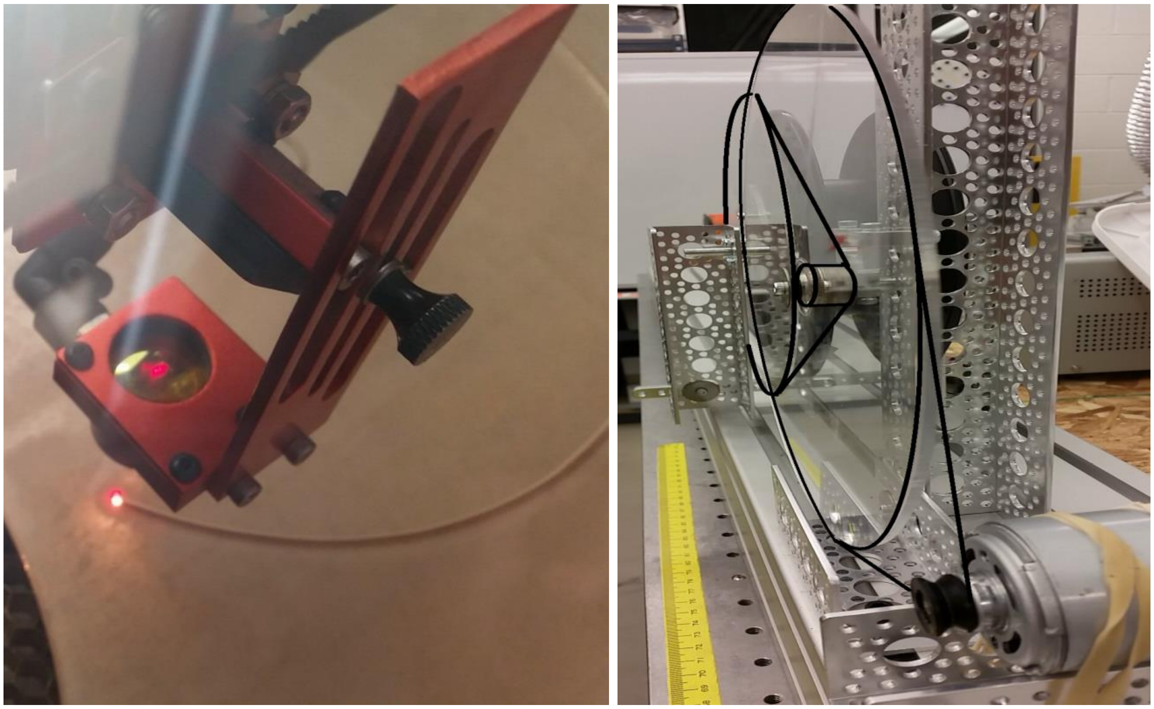

Figure 6.3 Drive wheels being cut from acrylic (left) and mounted as a transmission (right), black lines added to illustrate transmission wheel function.

This procedure of measuring the RPM of a hand-spooled filament and comparing it to direct-drive RPM can be used to calculate the necessary gear reduction regardless of filament material, spool size, or drive system.

7. Tungsten Powder Infusion

In order to accurately measure the effects of tungsten powder in the extrusion process, tungsten powder was initially added to the plastic filament by pre-coating ABS pellets rather than a metered hopper. Pellets were weighed before being placed in an oven and heated to 175˚C for 10 minutes. An amount of tungsten powder equal to 9-times the weight of the pellets was then added to the hot pellets to achieve the ideal 90% tungsten by weight. The coated ABS pellets were then shaken to improve coating and cooled to room temperature. Leftover tungsten powder was sifted out of the coated pellets. Both the coated pellets and the remaining tungsten powder were weighed to determine the actual tungsten-to-ABS ratio. Figure 7.1 displays photos of the process, and Table 7.1 displays measured weights for three trials.

Figure 7.1 ABS pellets on tungsten powder (left) are covered (right) before being heated.

Table 7.1 Weights of ABS and tungsten for 3 coated ABS trials, accurate to ±0.0002 kg.

Trial	Pellets (kg)	Tungsten for 9:1 ratio (kg)	Added Tungsten (kg)	Coated Pellets (kg)	Remaining Tungsten (kg)	% Tungsten by Weight
1	0.0162	0.1458	0.1458	0.0222	0.1356	27.03%
2	0.016	0.144	0.1444	0.0232	0.1342	31.03%
3	0.016	0.144	0.1444	0.0202	0.1386	20.79%

Qualitatively, the final pellets are harder and gray from the coating, as Figure 7.2 shows. The weight percentage for these trials is well below the optimal 90% by weight, but lower weight percentages may be advantageous in learning appropriate extrusion conditions for the filament. The process can also be streamlined, as exposed pellets in the third trial did not adhere to any powder when shaken, and instead turned yellow from the heat. To optimize coating, the pellets need to be completely buried in and surrounded by powder. Powder use can also be reduced by re-using any tungsten that does not adhere to the pellet surface.

Figure 7.2 Coated pellets are gray and hard, often stuck together from the baking process. They are easily sifted out of the remaining tungsten powder.

8. Future Work

To determine the feasibility of the coated ABS approach to producing tungsten-infused filaments, two tests should be run with the . In the first, only the coated ABS pellets should be added to the Filabot hopper. The Filabot should then be purged and a regular ABS filament should be extruded to determine if any damage to the hopper has occurred. The second experiment should be to add the coated ABS pellets to the Filabot hopper along with the remaining tungsten powder to produce a 90% mixture by weight. The Filabot should then be purged again to determine any damage caused by the tungsten. These two tests should give an inform the next steps in creating a consistent filament with the necessary tungsten-to-ABS ratio.

Once a method for tungsten-infusion has been developed, the next stage of this project is t o implement feedback loops to automate filament production. A logic analyzer should be used to electronically read diameter measurements from the Filameasure. Arduino control should also be implemented to control the Filabot & spooler speed, allowing testing to determine the effects of temperature, extruder speed, and spool speed on filament diameter.

Once construction is completed, the apparatus will be used as a test bed for ABS printing. This relatively easy-to-extrude material will create a procedure for testing and optimizing more exotic filaments such as the Tungsten-infused filament and biodegradable PHA.

The final stage of the project is to begin printing and optimizing Tungsten-infused filaments before making final prints with the optimized filament. These initial prints can then be tested empirically to determine how they compare with machined Tungsten detector parts and the brass detector masks used by the Hampton University Proton Therapy Institute (Deconinck, 2015).

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