Plastic Filament Extrusion System for Use with a 3D Printer

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Executive Summary

The objective of this project was to produce plastic filament suitable for use with RepRap 3D printers from raw plastic pellets or recycled plastic waste for the UBC Rapid student team. The specifications for the filament required that it be of similar quality to commercial filaments, smooth and with minimal bubbles with a constant diameter of about 3mm.

To accomplish this end, a prototype plastic extruder was designed, constructed and tested. The prototype was tested running at different speeds and temperatures to determine a good operating point. The investigation showed that extrusion of plastic filament of comparable quality to commercial filaments is possible with careful operation. The diameter is the most critical feature and is dependent on the rate at which the filament is drawn away from the die as well as a steady input to the heating pipe. With an outfeed mechanism, the filament could be drawn at constant rate to form a constant diameter.

The prototype showed several ways in which extrusion could be made more efficient in later designs. The recommendations leading from the testing of the prototype include isolation of the hopper from the heating area to prevent clogging by partially melted plastic and lengthening the heating area to allow for full melting of the plastic and steady flow to extrude for homogeneous filaments.

Table of Contents

List of Figures

List of Tables

Introduction

3D printing is a relatively new technique of manufacturing an object directly from a set of computer drawings. There are various methods of 3D printing. One such way is by melting and laying plastic filament down to slowly build up the model in layers in a process known as "fused filament fabrication" (RepRap Wiki). The downside to 3D printing is the cost associated with it. After a 3D printer is constructed, the main expense is the plastic filament required to print parts. The plastic filament can cost up to $50-$60 per kg for PLA plastic. Due to this, there are many groups that wish to try and lower the cost of 3D printing. UBC Rapid is a student team working on building RepRap printers that wants to reduce the cost of 3D printing so that it can be readily available to students and faculty of University of British Columbia.

In order to bring down the cost, UBC Rapid wants to find a cheaper way of obtaining the plastic filament that the 3D model is made from. Therefore, UBC Rapid has asked the project group to devise a method that would allow the filament to be made for much cheaper. It was decided that the best way is to extrude the filament from much cheaper plastic granules which sell for less than $10 per kg. Plastic extrusion is a well developed process so the goal was to build a small scale version of current industrial extruders.

During the course of the project, a fully functional plastic extruder was built. The extruder was built in the project lab and measured around 50cm in length. After testing the extruder, the group was able to gain a better understanding of the extrusion process and came up with a set of recommendations on how to develop a better second prototype. A second prototype could not be built before the project deadline.

The plastic extruder had to be designed so that it would run at the same time as the 3D printer. This way, the extruded filament would feed directly into the printer nozzle. The UBC Rapid team then wanted to see if it was possible to control the quality of the plastic as it was extruded so that the 3D model could have a varying stiffness throughout it giving it flexible joints. They would also like to eventually be able to recycle waste plastic using a shredder and reuse it with the extruder. Due to time constraints, the project group was only able to investigate the extruder and were not able to work on changing the plastic qualities of the filament or design a plastic shredder for recycling waste plastic.

This report will go into detail about the theory behind plastic extrusion employed in building the extruder and the methods used to accomplish extrusion. Then, the report will cover observations on how the actual extruder operated and the results that were obtained from it. A section is included which summarizes the final project deliverables and the items purchased for the extruder. Lastly, recommendations are given based those observation on the how a second prototype extruder can be improved.

1. Discussion

a. Theory

The construction and operation of the plastic extruder is largely based on existing designs used in both industrial and hobby applications. The basic mechanism is comprised of a screw that transports raw plastic pellets from a hopper through a heating zone in a metal pipe where the plastic is melted. The raw plastic pellets are gravity-fed from the hopper into the screw. Inside the pipe the molten plastic is forced through a die at the end of the pipe to form a filament. The extruded plastic can be drawn from the die to determine the final diameter of the filament. The die is shaped to form the extruded plastic into the desired cross-section. Figure 1 below shows a schematic of the basic extrusion system.

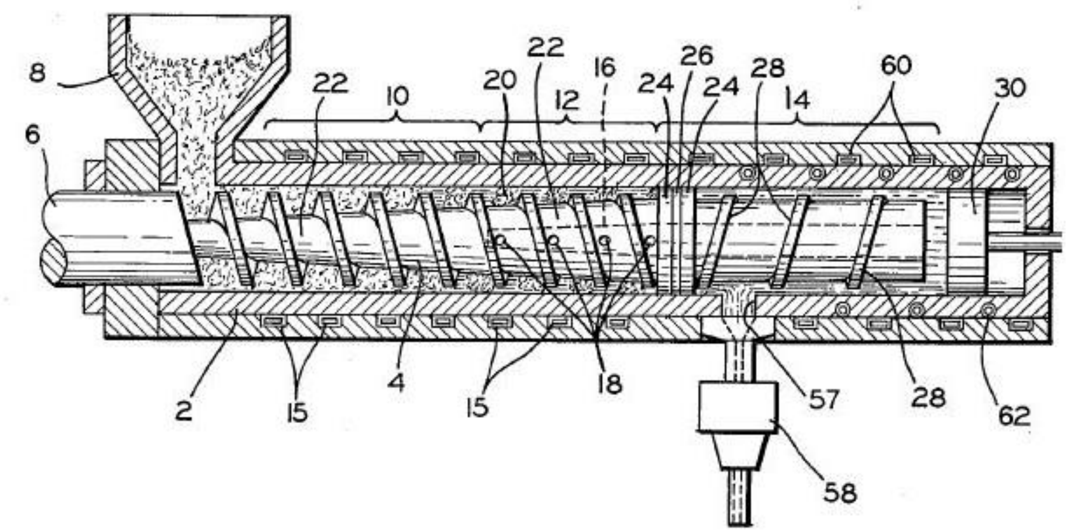

Figure 1- Schematic of plastic extrusion device. Hopper at top left feeds plastic granules into the screw which conveys them through the heating zone and forces the molten plastic through the die. (Adapted from US Patent 4118163, Plastic Extrusion and Apparatus, by Soo-Il Lee)

The application of this method of plastic extrusion was demonstrated on a small scale by the homemade plastic extrusion system seen in Figure 2 below.

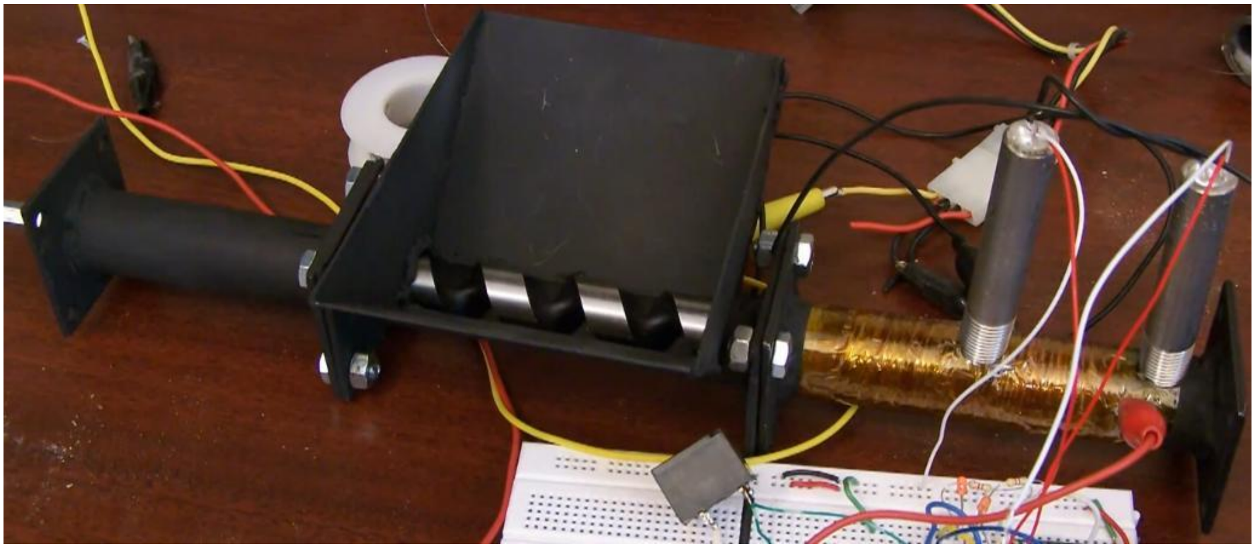

Figure 2 - Homemade plastic extrusion system (Screen capture of Youtube video by web4deb, see reference "Homemade Plastic Extrusion System", 2010)

The temperature of the melting zone is dictated by the variety of plastic to be extruded. For the polylactic acid (PLA) pellets provided by the project sponsor the melting temperatures are 200 and 210°C for types 3001D and 4043D respectively (Ingeo Biopolymer 3001D, Ingeo Biopolymer 4043D). The speed at which the screw is driven is governed by the power delivered to the heaters to fully melt the plastic as it is pushed through the heating zone.

b. Methods and Equipment

The basic design for the extruder was inspired by the homemade plastic extruder shown in Figure 2 above. The specifications for the project group's extruder required that it be able to produce a constant diameter filament of 3mm and it had to extrude at a rate of approximately 5mm/s. The prototype that was constructed is shown in the Figure 3,Figure 4Figure 5 following.

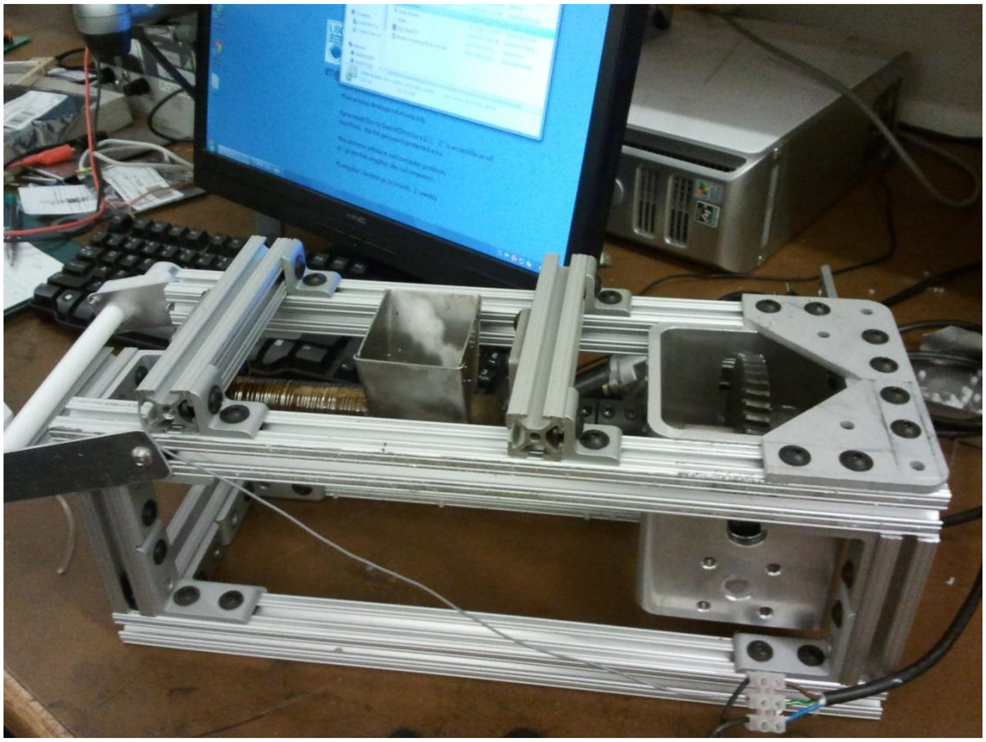

Figure 3- Plastic extruder prototype. Gearbox at right, hopper in center, and outfeed roller at far left.

Figure 4- Close-up of hopper and heating tube with NiChrome heating wire.

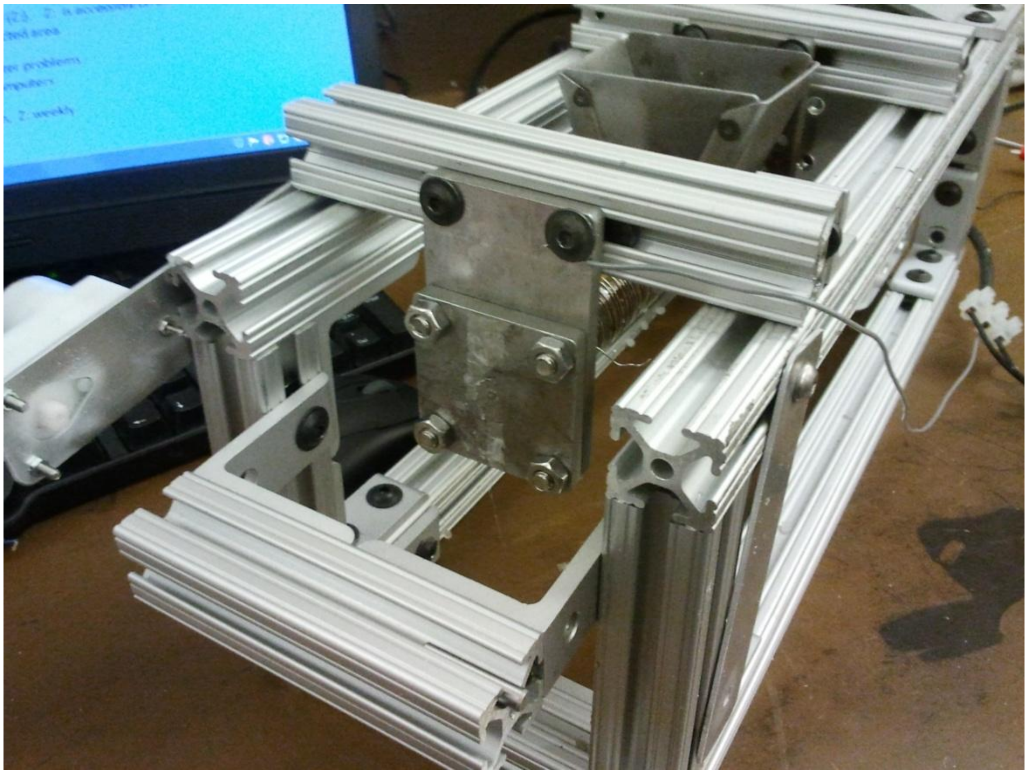

Figure 5- Close-up of extrusion die.

The screw that is used for the extruder is a ¾" wood auger drill bit. The screw is driven by a windshield wiper motor which has the speed stepped down by a 40:1 worm gear box. The roller at the outfeed end of the extruder as seen in the left side of Figure 3 draws the filament out at a constant rate.

The extruder body and gear box were supported by an 80/20 frame. The 80/20 frame allowed for easy assembly and adjustment. The gear box was a part found already assembled in the project lab. It just had to be slightly modified to be added to the extruder. The motor was powered by a manual power supply from the project lab and was run at up to 12V. The hopper, heating tube, and flanges were made using the waterjet cutter and were then welded together. The die was custom made using the waterjet cutter as well and was attached to the extruder through use of four screws. This allowed for the die to be easily changed if needed.

The type of heater used was changed during the course of the project. At first, three silicon heaters were used which output 30W of heat each and ran on 110 V AC. The silicon heaters were attached to the extruder tube using a special heat resistant adhesive. The voltage was controlled through use of a manual AC voltage regulator. A thermocouple was used to measure the inside temperature while an infrared thermometer was used to measure the outside temperature. These silicone heaters provided insufficient power to fully melt the plastic. Though rated to 210°C the heaters only provided enough power to achieve temperatures up to 110°C inside the tube and 150°C outside. The melting point of the PLA plastic being used, 3001D from Jamplast, was 200°C. Insulation was added to the outside of the tube but that only increased the temperature to 150°C inside the tube. The temperature was measured using a thermocouple which output the temperature in °C as mV. The heat from silicon heaters caused the plastic to melt somewhat, but not enough to allow extrusion through the die. The plastic would remain in the tube and finally cause the motor to stall when it couldn't provide enough torque.

To provide more power the heating system was switched to NiChrome wire. The tube of the extruder was wrapped in Kapton tape to electrically insulate it. Then, 26 BNC wire was coiled around the tube. The 26 BNC NiChrome wire had a resistivity of 0.088Ω/cm. Initially, 1 m of NiChrome wire was used and was tested with an AC voltage of 25V but the wire drew too much current, which caused it to become red hot in localized places and melt through the tape holding it in place. For the next attempt, 3.6m of NiChrome wire was used to increase the resistance and therefore decrease the current.

c. Results

Initial tests employed the silicone heaters to melt the plastic. Though rated to 210°C the heaters only provided enough power to achieve temperatures up to 110°C inside the tube and 150°C outside. The melting point of the PLA plastic being used (3001D from Jamplast) was 200°C. Insulation was added to the outside of the tube but that only increased the temperature to 150°C inside the tube. The heat from silicon heaters caused the plastic to melt somewhat, but not enough to allow extrusion through the die. The plastic would remain in the tube and finally cause the motor to stall when it couldn't provide enough torque.

More power to heat the extrusion tube was provided by switching to NiChrome wire as the heating element. With 3.6m of wire, run at 60V, drawing 2.0A the interior of the tube reached 210°C. This provided 120W of power, fully melting the plastic and successfully extruding filament.

The resulting extruded filaments are shown in Figure 6 below alongside a commercially produced PLA filament on the right.

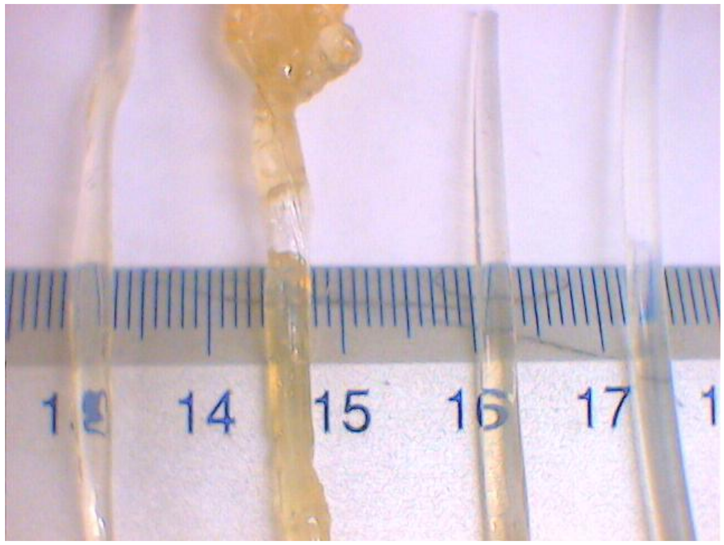

Figure 6- Extruded PLA filaments, far right shows commercial filament for comparison.

On the left, the first sample shows PLA extruded at low speed (DC motor supply at 7V) with the NiChrome wire supplied with 60V (measured external temperature approximately 210°C).This filament shows a smooth surface and homogeneous interior with a few small bubbles. The second from the left shows PLA filament extruded at a higher rate with the DC motor supply at 12V and the heater supply set to 60V (external temperature again measured to be approximately 210°C). This filament shows a rough surface and interior with a yellowish discolouration and bubbles in the interior. The third filament from the left shows PLA filament extruded again at a slower rate with the DC motor supply at 7V with the NiChrome wire supplied with 60V. This run was much longer, approximately 30 minutes with the highest measured temperature reaching 250°C. This filament shows a smooth surface and homogeneous interior with few bubbles. All filaments showed a similar flexibility to the commercial filament. For all filaments the diameter varies due to drawing the filament away from the die by hand.

The samples of extruded filament shown in Figure 6 above demonstrate that the extrusion rate and temperature are important in producing quality filament. When the extrusion rate is too high, the resulting filament is rough and non uniform. At lower extrusion rates and correct temperature the filament is homogeneous and smooth. The temperature can exceed the melting temperature to a point without effect on the quality of the filament.

Aside from the quality of filament, the performance of the prototype extruder was also under investigation. During extrusion, the heat from the NiChrome wire wrapped around the pipe is conducted to the hopper. If a large amount of raw plastic is placed in the hopper this causes the plastic in the hopper to begin melting and clog the inlet to the pipe. Also, the melted plastic cannot be removed from the pipe if the pipe and plastic is allowed to cool. Finally, after long operation the frame of the extruder becomes hot through contact with the heating pipe.

2. Conclusions

Extrusion of high quality filament requires that the temperature and extrusion rate be appropriately set. If the extrusion rate is too high the raw plastic will not fully melt and small solid pieces will cause roughness and bubbles in the resulting filament. This condition can be avoided by decreasing the motor speed for an appropriate temperature. This allows enough heat to be delivered to the plastic pellets, fully melting them and resulting in a homogeneous and smooth plastic filament. Experimentation showed that the prototype could extrude good quality filament with the motor DC power supply set to 7V and the temperature in excess of 200°C, the melting point of the PLA pellets in use for the experiment. The final diameter of the filament is determined by both the size of the die and the speed at which the hot filament is drawn away from the outlet.

For efficient and robust continued operation of the extruder the hopper must be isolated from the heating zone so that the raw pellets do not begin to melt in the hopper and clog the inlet. With greater isolation between the hopper and the heating zone a larger volume of plastic can be added to the hopper to extrude more filament without worry of clogging the inlet to the heating pipe. Also, decreasing heat conduction between the heating pipe and the frame would improve the safety of the extruder and also increase the efficiency by limiting power loss. To remove the excess plastic when the extrusion is complete the pipe should be cleaned before the heating pipe cools or simply left to cool and reheated when the extruder is used again.

3. Project Deliverables

With the completion of this project, the project group will be able to give UBC Rapid a preliminary prototype which is fully functional. While the extruder is still not able to produce a filament that meets the required diameter specification, the project group has compiled a list of recommendations and changes to the first prototype that will help improve the filament quality. The group also has a set of SolidWorks drawings of the extruder to go with the prototype. With the completion of this report, the project group will have no more ongoing commitments to the project.

Financial Summary

Table 1 – List of purchased items

#	Description	Quantity	Vendor	Cost	Purchased by
1	¾" x 7½" Auger Drill bit	1	Coe Lumber Supply	$12.99	Project Group
2	Shaft Coupler (3084K32)	2	McMaster Carr	$24.20	Project Lab
3	Silicon Heaters (35765K465)	3	McMaster Carr	$24.67	Project Lab
4	Silicon-Rubber Adhesive (74515A32)	1	McMaster Carr	$11.75	Project Lab
5	PLA Plastic	3	Jamplast	N/A	Project Sponsor
6	NiChrome Wire (8880K76)	1	McMaster Carr	$11.97	Project Lab

4. Recommendations

In order to improve the quality of the filament being extruded, the project group has two recommendations. The first recommendation is that the heating zone of the extruder tube be extended. The group observed that the longer the plastic was heated, the smoother the final product was and that it contained less air bubbles. The second recommendation is to isolate the hopper from the heating zone to prevent the hopper from heating up. The group found that since the hopper was adjacent to the heater with no form of insulation, the hopper would heat up and preheat the plastic before it entered the tube. This caused the plastic to clump up at the entrance and cause the flow rate to vary while also requiring intervention to break up the clog. Since the flow rate would change, the filament would have a varying diameter as it was extruded due to the fluctuating mass flow rate.

In order to accommodate these recommendations, several structural changes to the extruder need to be made. The first is to spatially separate the hopper tube from the heating tube and to place a piece of insulating material between the two tubes. In the current design, the hopper and heating tube are essentially one piece. The two tubes would be joined together the same way that the die is attached to the tube through the use of flanges. By having the insulation between the two tubes, the heat from the heating tube would not conduct down to the hopper tube. If the hopper is no longer heated, then the plastic should no longer clump together in the hopper. To extend the heating tube, other parts would need to be extended as well. The drill bit acting as the feed mechanism would need to be longer as well as the frame supporting the extruder. The spacing between the end of the drill bit and the die should remain the same at approximately 25mm.

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