Granulate extruder for the Cr-10s

Manufacturing and testing of a granulate extruder for the Cr-10s 3D printer

Tobias Jansson

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Ändamålet för detta examensarbete var att bygga och testa en granulatmatad extruder åt en Creality Cr-10s 3D printer. Merparten av delar tillverkades hos Yrkeshögskolan Arcada och ett fåtal delar köptes in utifrån. Dassault Systèmes Solidworks programvara och skolans 3D printrar användes för plast delar och metalldelar tillverkades enligt behov. Med hjälp av volymflödes analys baserat på Crawford 2005 och flera andra källor mättes volymflödet av den ursprungliga filament extrudern. Volymflödet mättes flera gånger med olika skruvhastigheter för att finna en optimal skruvhastighet för extrudern i relation till den originella extrudern. De olika skruvhastigheterna ändrades genom g-kod-manipulering av printerns egna inställningar. Resultaten var varierande men indikerade att optimal skruvhastighet låg kring 1600 till 1900 steg per millimeter utmatat plast. På grund av externa orsaker kunde slutgiltigt testande och optimerande av printern inte utföras. Slutsatsen är att med optimering av granulat storlek, skruv längd, skruvhastighet kunde extrudern potentiellt nå samma pålitlighet och kvalitet som en traditionell filament-extruder.

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Abstract:

The purpose of this thesis was to build and test a granular extruder for a Creality Cr-10s 3D printer. Most of the parts were manufactured at Arcada University of Applied Sciences and a few parts were purchased from outside. Plastic parts were made using Dassault Systemès Solidworks software and 3D printed, metal parts were made according to need. Using the volume flow rate analysis based on Crawford 2005 and several other sources, the volume flow rate was measured by the original filament extruder. The volume flow was measured several times at different screw speeds to find an optimal screw speed for the extruder in relation to the original extruder. The different screw speeds were achieved by g-code manipulation of the printer's own settings. The results were varied but indicated that the optimum rotation speed was around 1600 to 1900 steps per millimeter of plastic. Due to external reasons, final testing and optimization of the printer could not be performed. The conclusion is that with optimization of granule size, screw length, rotational speed, the extruder could potentially achieve the same reliability and quality as a traditional filament extruder.

Keywords:	Granulate extruder, Granulate, Extrusion, 3D-Printing, Creality Cr-10s, Volume flowrate
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Tiivistelmä:

Lopputyön päämääränä oli rakentaa granulaattisuulakepuristin eli granulaattiekstruuderi, ja testata sitä Creality Cr-10s 3D-printterissä. Suurin osa granulaattisuulakepuristimen osista on rakennettu ammattikorkeakoulu Arcadassa. Loput osat on ostettu ulkopuolisilta. Muoviset osat on suunniteltu Dassault Systemèsin Solidworks-ohjelmalla ja tulostettu 3D-tulostimella. Metalliset osat valmistettiin tarpeen mukaan. Virtaaman eli tilavuusvirran analyysin tekemiseen käytettiin monia lähteitä, kuten Crawford 2005. Virtaamaa mitattaessa käytettiin alkuperäistä filamenttisuulakepuristinta. Mittaukset suoritettiin moneen kertaan eri ruuvin nopeuksilla optimaalisen ruuvi─suulakepuristin-suhteen löytämiseksi. Eri ruuvinopeuksiin päästiin muokkaamalla printterin omaa g-koodia. Tuloksissa oli vaihtelevuutta, mutta saatu tieto viittaasi siihen, että optimaalisin pyörähdysnopeus ruuvilla oli 1600-1900 askelta, per millimetri muovia. Ulkopuolisten syiden takia, lopputestausta ja printterin optimointia ei ollut mahdollista toteuttaa. Loppupäätelmä on, että granulaattien koon, ruuvin pituuden, ja ruuvin pyörimisnopeuden optimoiminen voi mahdollistaa granulaattisuulakepuristimen pääsemistä, niin luotettavuuden kuin laadun osalta, samalle tasolle perinteisten käytössä olevien filamenttisuulakepuristimien kanssa.

Avainsanat:	Granulaattiekstruuderi, granulaatti, muovipelletit, suulakepuristus, ekstruusio, 3d-printtaus, Creality Cr-10s, virtaama, tilavuusvirta.
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FOREWORD

The idea for this thesis originally came from the need for pellets to be turned in to filament for a 3D printing project at campus. With additive manufacturing becoming more widespread consuming more plastic and leaving more failed prints ways to reuse “wasted” plastic is needed. It has been thoroughly enjoyable to explore the option of building and using a granulate fed extruder on a 3D printer and I would have liked to continue testing which was unfortunately not possible due to the covid-19 pandemic and the closing of schools and campuses around the country.

I would finally like to thank everyone who encouraged me and showed interest during the process of building, testing and troubleshooting the extruder. I’d also like to thank my supervisor Harri Anukka and my examiner Silas Gebrehiwot. I’d highly recommend anyone to work with them.

Thank you all.

Tobias Jansson
Närpes 2020

1 INTRODUCTION

With the need for making filament out of pellets when nobody is around to make the filament, a granulate fed extruder on a 3D printer could be the solution. There are a few reasons that make using pellets instead of a traditional filament lucrative for the additive manufacturing process. The first one being the price of pellet comparable to finished filament. The second one is the large selection of materials, colors and additives available. Potentially higher quality due to fewer heating and cooling cycles which degenerate the quality of plastics over time being the third. Lastly is the ease of using recycled materials and decreasing the waste material from additive manufacturing process.

The objectives of this thesis work are:

- Build a functional plastics extruder from available materials that the average person could make on his own.
- Attach the extruder to a commercial 3D printer, in this case the Creality Cr-10s.
- Maintain a smaller footprint than “commercially available” and alternatives available for manufacturing off the internet (such as the Pulsar Pellet Extruder, or other D.I.Y. extruders available on e.g. thingiverse.com).
- Design a printer profile suitable for the extruder as built in Ultimaker Cura profiles are not suitable for pellet extruders.
- Print using granulate.

2 THEORY

2.1 PLASTIC EXTRUSION MACHINE

Plastic extrusion is a commonly used method in manufacturing plastic parts. Injection molding, filament manufacturing, 3D printing and general plastic extrusion all work on the same theory. In the simplest form solid plastic goes in, is transported, melts and is extruded. This chapter treating granulate fed extrusion is based on the work by R.J. Crawford (2005) specifically chapter 4 Processing of Plastics.

A granulate extruder consists of a hopper attached to a barrel wherein an extrusion screw lies. The granulate falls down in to the screw and is transported along the length of the extrusion barrel where the granulate is ground up, heated and compressed before being extruded through a die. In conventional plastic extruders the extrusion direction is generally horizontal and the granulate feed direction is vertical. This helps with accurate and consistent feeding.

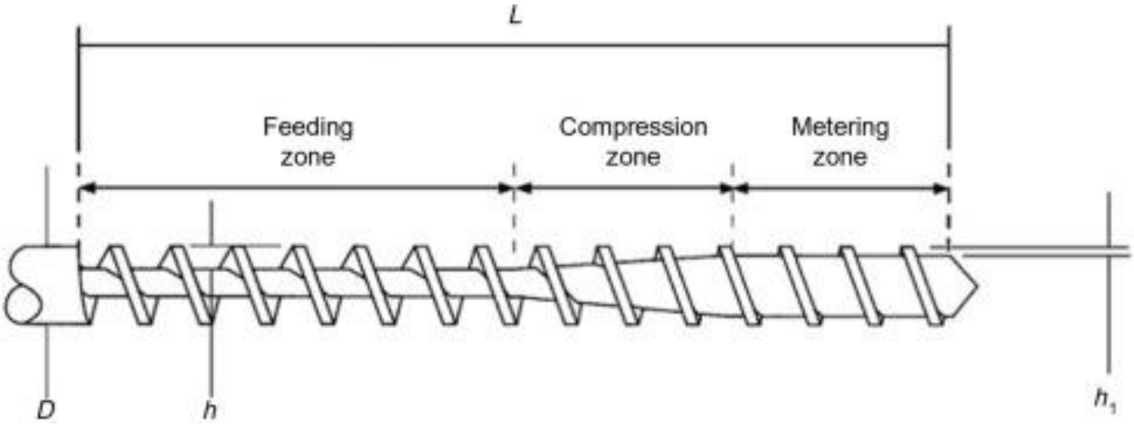


Figure 1. Features of a typical extrusion screw (Yuan and Liu, 2014, figure 5)

A plastic extruder has 3 general zones. In the first zone, the feed zone, the plastic is simply warmed up and conveyed to the next zone, the screw depth and pitch generally stay the same during this zone.

The compression zone follows the feed zone where the screw depth is usually decreased to compress the plastic and force out any empty spaces in between individual plastic particles causing a more homogenous plastic melt without air bubbles in it. At this point friction between the plastic particles and the barrel heating has already melted the plastic.

The third zone is the metering zone where the screw depth is also often constant and the same or slightly shallower than in the compression zone. The metering zone aims to transport the molten material at a constant temperature, viscosity and pressure through a filter plate and out through the die. Typically, the screw stops a short distance before the filter to allow for the accumulation of plastic and pressure build up before (and after) the filter for a more even flow out through the die. (Crawford, 2005)

Though the appearance (profile) of the extrusion screw may vary a lot the general principle of plastic conveying stays the same. Industrial screws also perform a grinding function breaking up the granulate even further to quicken the melting procedure of the granulate inside the barrel.

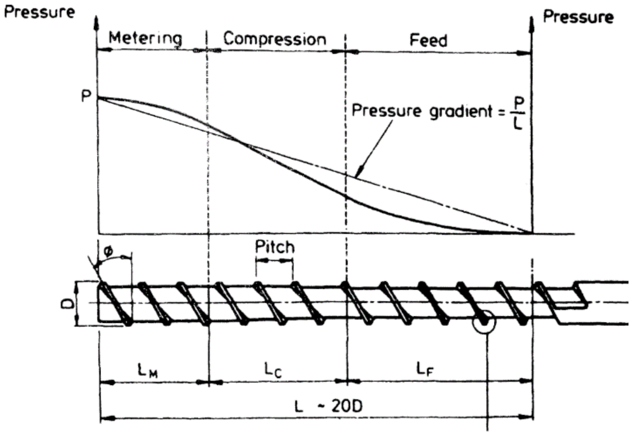


Figure 2. Pressure gradient (Crawford, 2005, Fig. 4.2, P. 246)

As the extruder to be built will be of fairly low complexity the screw will have constant pitch and flange depth in contrast to many purpose-made extrusion-screws.

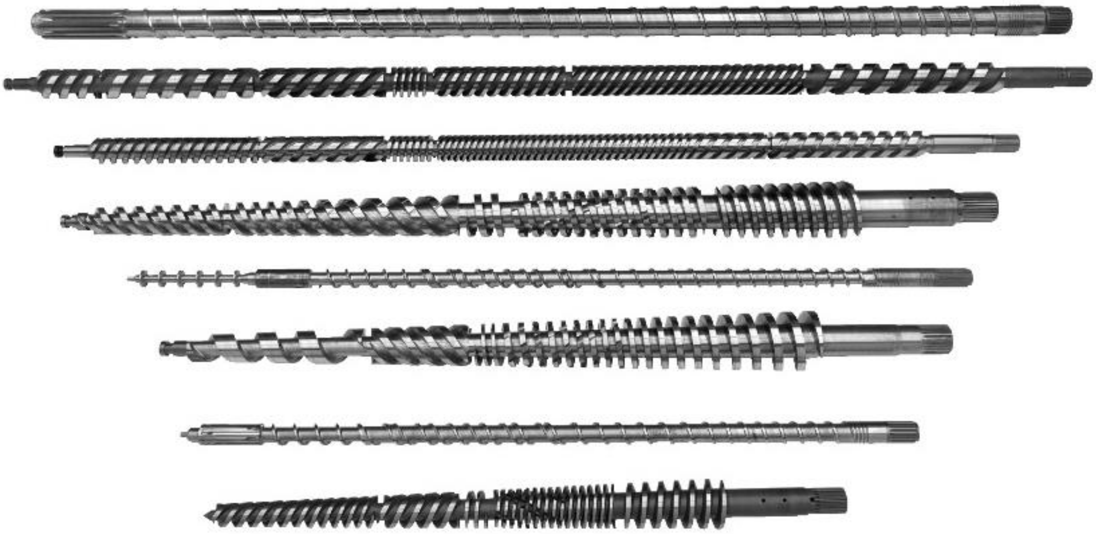


Figure 3. Extrusion Screws collection, (Extrusion Screws Machining, Danobat)

2.2 ADDITIVE MANUFACTURING

Additive manufacturing is the term for three-dimensional manufacturing of objects, adding layer by layer on top of each other to achieve the final three-dimensional shape. The term 3D printing encompasses many different ways of achieving the layer by layer build-up of material.

The most common method, Fused filament fabrication (FFF) or more commonly known as fused deposition modelling (FDM) which belongs to the category of filament extrusion. Another category is stereolithography (SLA) which uses a liquid resin and an ultraviolet light to harden the resin layer by layer and in that way building the three-dimensional model. Finally, there is Selective laser sintering (SLS) which uses lasers to fuse particles together with high heat, usually metal in powder form, layer by layer to build a three-dimensional object. These three, FDM, SLA and SLS make up the vast majority of the 3D printing market. (Griffey, 2014)

Common for all these methods of manufacturing is that they all rely on CAD (computer aided design) models which are run through software known as slicers which slices the model into layers according to the settings selected in the software. Different printers use different slicer software however, there are few alternatives on the market that work with a multitude of different printers. The slicer also generates supportive structures (if the setting is enabled) to aid in the manufacturing and giving a higher quality end product. With the object in the slicer g-code can be generated and sent to the 3D printer which can then usually be left alone until the manufacturing process is done (Noorani, 2018), however periodic check-ups are recommended as failures may still occur.

2.2.1 Creality Cr-10s

Creality is a fairly new competitor on the 3D printing market and in 2014 made their entry. The first well recognized printers around the was the Creality Cr-10 series of printers in 2016 followed in 2017 by their Ender models. Their low prices, user-friendly assembly process, build quality, and often high print surface and build volume made them highly appreciated in the 3D printing community.

The Creality Cr-10s is an open 3D printer meaning it is not inside an enclosure making it easy to work on, modify and observe. The Cr-10s has; a build volume of $300mm \times 300mm \times 400mm$, control box separated from the printer, double Z-axis for higher stability in the Z direction as well as a Bowden-type extruder that allows a lighter extruder moving around. (Mensley, 2018)

Figure 4. Creality Cr-10s (Mensley, 2018)

2.3 PLASTIC FLOW AND FLOWRATE

Plastic enters the extruder in its solid state, as it moves inside the extruder barrel it softens and at some point, it melts. The theory of plastic flow states that an initial thin film of molten plastic is created along the extruder barrel, with an axial velocity of zero. The thin film is scraped off by the extruder screw and pushed forward. The now molten plastic interacts with yet unmolten plastic particles and helps melting them too.

When molten plastic is inside the extruder barrel it tends to (partially) stick to either the barrel wall or the screw, the latter being undesirable as it would result in zero axial velocity (velocity in the extrusion direction) and therefore zero volume extruded. The plastic sticking to the extrusion barrel rather than the screw is more desirable as the bulk of the material would still be transported forward inside the barrel with the flanges of the extrusion screw. The plastic flow is laminar with the highest velocity being nearest the center of the extrusion screw. (Crawford, 2005)

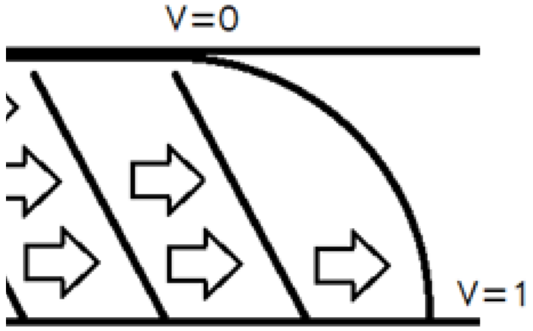


Figure 5. Representation of velocity inside extruder barrel

The flowrate, or volume flowrate ($\dot{V}$) describes a volume of material flowing past a point during a given time. Often this is cubic meters per second, minute or hour but for this thesis the flowrate is always in the unit of cubic millimeters per second ($mm^3/_s$). According to the international standard ISO 1133 the melt volume flowrate should however be measured in cubic centimeters per 10 minutes. (Strömvall and Lundh, 2019)

The volume flowrate can be determined by first measuring the time it takes for the extruder to extrude a mass of material. The mass can then be divided by the density which gives the volume (Seppänen et al., 2006, p. 131). The volume divided by time gives the volume per unit time which is volume flowrate.

$$\frac{m}{p} = V \rightarrow \frac{V}{t} = \frac{\left(\frac{m}{p}\right)}{t} = \dot{V} \qquad (1)$$

The same equation with units gives the following equation.

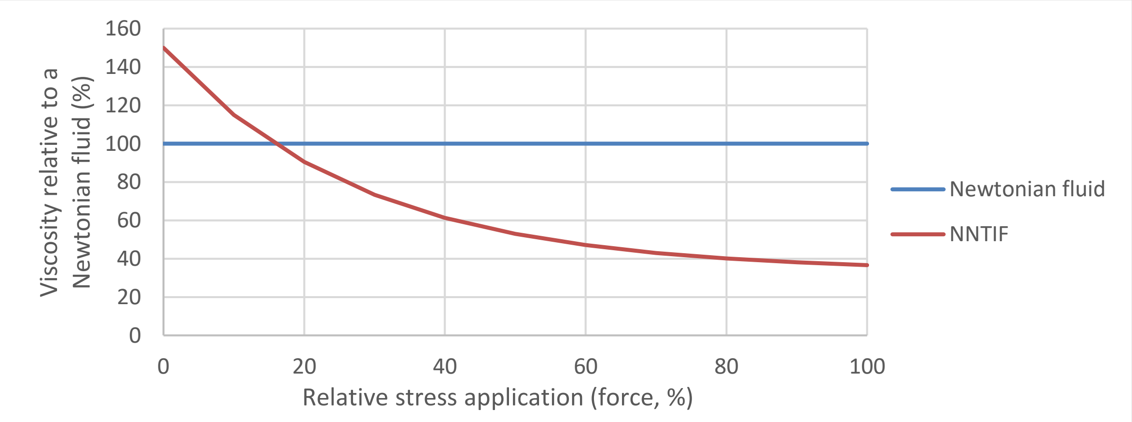
$$\frac{g}{g/_{mm^3}} = mm^3 \rightarrow \frac{mm^3}{s} = \frac{\left(\frac{g}{g/_{mm^3}}\right)}{s} = mm^3/_s \qquad (2)$$

Important to remember is using the correct density, as polymers have different densities depending on which state they are in. When measuring the solid material flowrate, the normal density is used and when measuring molten material, one should use the melt density.

In the same way that the structure of molecules inside a polymer affects the mechanical properties of a plastic it also affects the processing properties. As different polymers have different molecular structures, they have different mechanical and processing properties. Different manufacturers of the same materials and even the same material from the same manufacturer but different batches have a variation in their properties requiring adjustment for optimal results.

A material with high flow (low viscosity) is suitable for injection molding where plastic has to flow fast through small channels and fill a cavity in a short period of time. The same polymer might not be optimal for extrusion as the low viscosity might lead to leakage and backflow. Materials' behavior is correlated to the molecular weight distribution and the international standard ISO 1133 describes the methods of determining MFI (Melt flow index) which is useful in selecting plastics with the right properties (Strömvall and Lundh, 2019). For extrusion (and especially this build which will basically be an extruder rotated 90 degrees) a somewhat higher viscosity would be desired as the flow is more consistent and less affected by outside factors (e.g. gravity).

Non-Newtonian fluids are divided in to time dependent and time independent fluids. Polymer melts are usually non-Newtonian time independent fluids (NNTIF) and most polymer solutions are pseudoplastic fluids as they experience shear thinning (Polymerdatabase.com, 2015). The effect of pressure (force) on a NNTIF's viscosity is shown in the graph below and is called shear thinning (Science Learning Hub, 2015). As for temperature, generally increased temperature results in lower viscosity.



Graph 1. Representation of a non-Newtonian time independent fluid shear thinning in comparison to a Newtonian fluid (Science Learning Hub, 2015).

In practice this means, higher RPM (rotations per minute) means more material in to the extruder and a higher pressure inside the extrusion barrel where the plastic's viscosity decreases due to stress application and temperature before flowing out through the nozzle.

3 METHOD

The philosophy behind the design is with minimal modifications and easily manufactured parts enable the handy person to manufacture a similar product him-or herself. The description of the parts made are in no particular order and from start to finish despite numerous improvements being done along the way resulting in a final product. Pictures will be provided of notable designs that did not make it as well as the final part. A short description of the general procedure is in order to give an overview of the whole build process with further in-depth details and pictures following in separate chapters.

The build started off with the machining of the extrusion barrel on the lathe. The cooling fins were roughly made the same thickness as the gap in between them. With the barrel done the bolt that was to hold the nozzle, heating block, bottom plate together was machined also in a lathe. The internals were drilled out to hold the 8mm extrusion screw and a 5.4 mm hole was left in the head of the bolt to allow for a thread for the nozzle to be made.

Following this the mounting bracket holding the extruder to the printer was designed as at this certain point the total height of the barrel and nozzle was known. The mounting plate was 3D printed after which the rods holding everything in compression was cut to length and assembled with nuts and washers.

The hopper was then designed and 3D printed and all of it was mounted to preliminary testbench where heating could be measured and manual screw rotation to test extrusion could be performed. The extrusion screw was then cut into suitable length leaving roughly 15mm extra for fitting before finally facing off the ends and creating an indentation in the top.

With the right hopper design the top tensioning plate was cut out from a piece of aluminum flat-bar and the required holes were made. Finally, the tensioning bolt was mounted to the lathe and given a cone shape to reduce the friction between the screw and the tensioning bolt. With all the parts manufactured and assembled mechanical testing started

3.1 PARTS

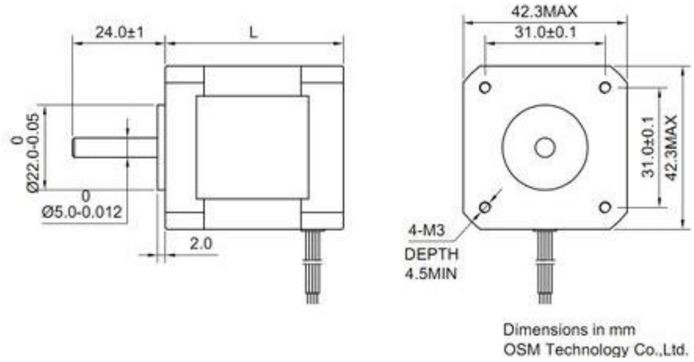
Plastic parts were designed using Dassault Systèmes Solidworks software and 3d printed, metal parts manufactured were made on the spot. The commercial parts used were;

- 8 mm Auger drill bit because of its similarity to an extrusion screw in that it has a large open volume due to the flute width and depth. Available in most hardware stores for less than 10€ excluding larger sizes.
- NEMA 17 stepper motor due to their compatibility with existing 3D printers, high torque, cheap price and wide availability. Available in specialized stores or online ranging from 15€-70€ depending on the model.
- 8 pin connection to connect to the existing socket on the Creality Cr-10s which is available on multiple websites for ordering from about 2€ all the way up to 10€
- 40 mm fan, available in most electronic stores as well as on E-bay for 2€-10€

3.1.1 MOUNTING BRACKET

The mounting bracket fulfills the purpose of linking the extrusion barrel, motor and hopper to each other as well as to the printer. Since the motor was to be mounted parallel to the extruder screw there needed to be a drive gear mounted to both the screw and motor axis. To connect these two a belt was used. The belt required the ability to be tensioned which description is available further down.

The key measurements for the mounting bracket were the dimensions of the NEMA 17 stepper motor as pictured in Figure 6. NEMA 17 Stepper Motor - RepRap, the lay-out of the mounting holes on the 3D printer, diameter of extrusion barrel and length of the timing belt driving the screw. Furthermore, the holes for mounting the motor were made such that the motor had room to slide and be locked in place with the screws once desired tension was achieved.



Dimensions in mm
OSM Technology Co.,Ltd.

Figure 6. NEMA 17 Stepper Motor - RepRap

The distance from the existing mounting holes on the 3D printer to the point of the nozzle was measured by first lowering the hot end to its home position using the inbuilt software then disassembling the original hot end and measuring the height from the print bed to the mounting points. This was done to make sure the nozzle of the new extruder would be at the right height to not damage the print bed if too low or be too high up for the plastic to be printed on to the print bed.

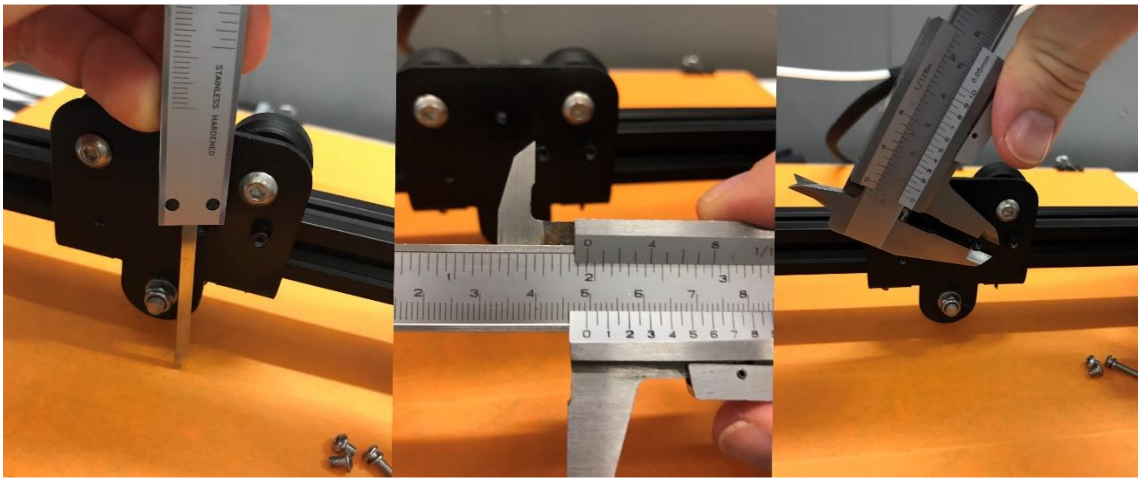


Figure 7. Measuring procedure

With the height from the tip of the nozzle to the center of the main mounting points determined the locations of the secondary mounting point were determined using trigonometry working outwards from the two main mounting points. A few sets of test pieces were printed to make sure the holes aligned and everything fitted together before the final version of the mounting plate was printed.

Figure 8. Hole alignment test pieces

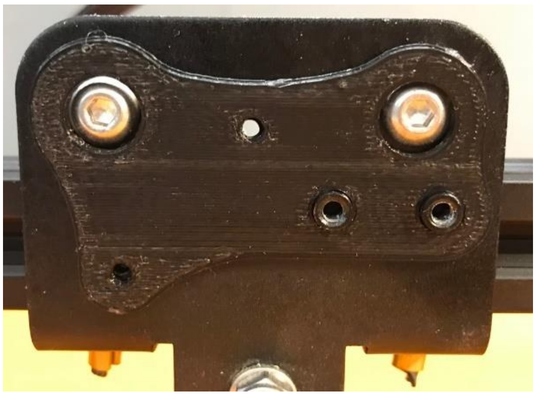


Figure 9. Test piece fitted

The mounting plates were 3D printed in ABS (acrylonitrile butadiene styrene) in a few variations. The early variations of the mounting plates (and other 3D printed parts) were made with a pink filament due to the lack of higher quality ABS filament. Both the mounting plates in *Figure 10. Two variations of the mounting plate* broke at some point during testing due to the lower quality ABS filament and were glued back together.

Figure 10. Two variations of the mounting plate

Figure 11. Final mounting plate

3.1.2 HOPPER

The hopper was modified the most times when flaws were discovered. The first design was a very simple cylinder with a conical shape inside to allow for pellets to easily slide down in to the feeding screw and a cut out for the belt to move in. The granulate had a tendency to get in between the driving belt and the gear preventing the screw from rotating reliably. The next issue noticed was the tendency of the screw to rise when plastic accumulated in the bottom of the heating barrel so another version of the hopper was made to allow for a tensioning screw to be added that prevented the extrusion screw from rising. This version of the hopper further prevented plastic granulate from getting in to the gear and in combination with the top plate holding a tensioning screw was more suitable to perform the task. Furthermore, extending the mounting thread rods to allow for holding a taller product together was needed.

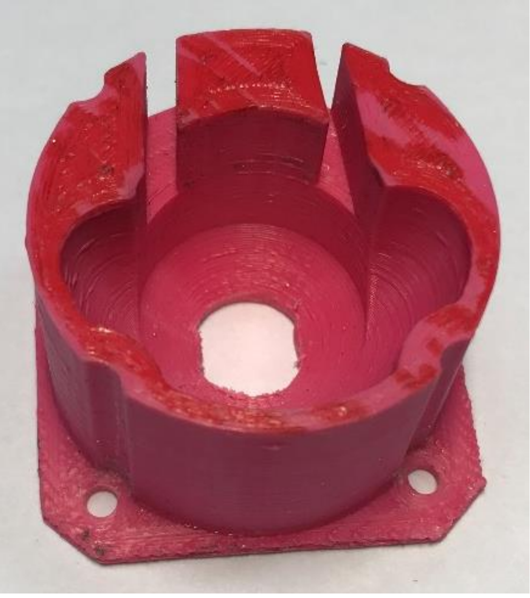


Figure 12. Early version of hopper

Figure 13. Mid version of hopper with separate feeding tube

The Final versions of the hopper featured a side mounted feed tube with a hole going straight to the bushing in which the pellets could fall down into the screw. The section where the gear and the belt were housed had to be completely closed off to prevent interfering from pellets with the pulley system as well as featuring a larger diameter hopper to hold more pellets.

Figure 14. Final version of hopper

There were a number of “bushings” manufactured from aluminum as part of the hopper to help the screw stay aligned with the extrusion barrel, at a height to allow for a small area of empty space at the bottom of the barrel where plastic could accumulate and be put under pressure. As well as keeping the drive gear and extrusion gear at the same height. From left to right is first to last version of the bushing. Important measurements were the inner diameter (8 mm in this case for this screw) as well as the height to get the gear to the right height, in this case 16 mm.

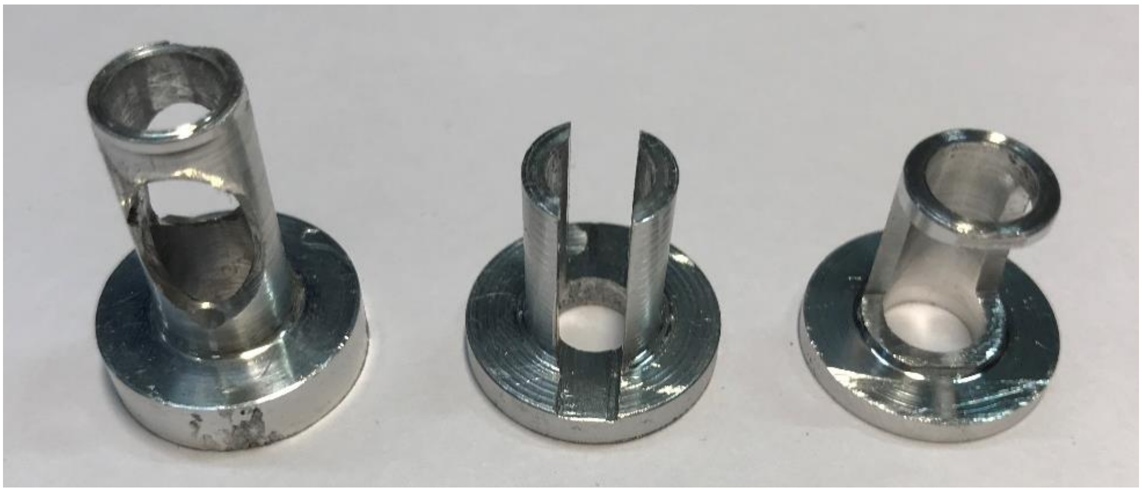


Figure 15. Aluminum bushings

3.1.3 BOTTOM PLATE

The bottom plate held the heating barrel in place in relation to the mounting bracket and was made out of a flat aluminum bar with a width of 40 mm and thickness of 6 mm. This piece of metal was selected purely due to its availability. The specifics were not important to the general functionality of the final extruder, however enough room for four M3 holes arranged at equal distance in a square-like pattern (with c-c measurements of 31 mm to keep the measurements consistent for ease of memorability and aesthetic consistency) was necessary. The hole in the center was 12 millimeters to fit over the nozzle and go in between the extrusion barrel and the heating block.

In *Figure 16. Bottom plate with rods* the M3 threaded rods are also visible, for this design they were made 125 mm long. The two cut-outs on the side are to make space for the wires from the two heating elements and the temperature sensor while also helping in inserting and removing them according to need.

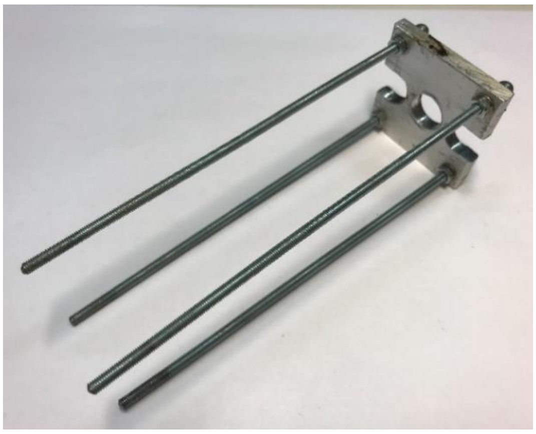


Figure 16. Bottom plate with rods

3.1.4 HEATING BLOCK

The first version of the heating block only had room for 1 heating element which was later discovered to be inadequate for the purpose due to the large amount of aluminum which transfers heat very well, as well as the cooling solution to prevent the extrusion barrel's top from melting the 3D printed mounting bracket. The second version of the heating block had slots for two 12 Volt 40 Watts heating elements to be inserted, this however required an external power supply to heat the second element. It was decided to use the second heating element only for heating the extruder to about 150 degrees Celsius from where the 3D printer's own heating element would heat it to the final temperature.

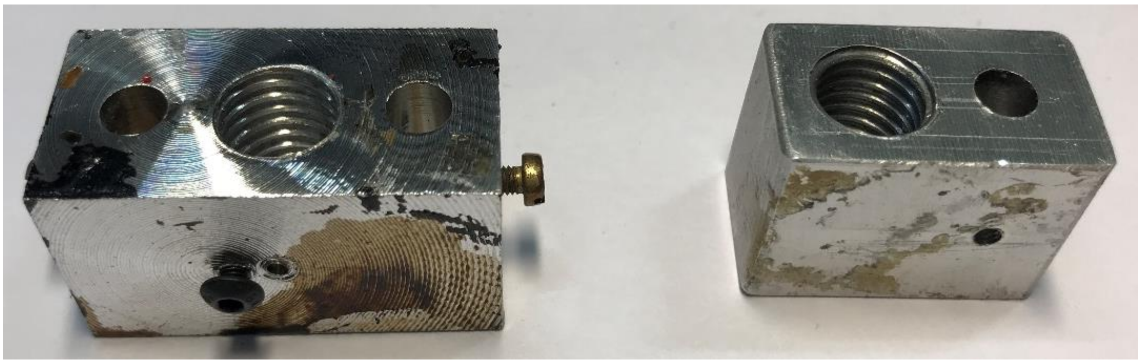


Figure 17. Heating blocks

Interesting side note is that many (if not most) commercial 3D printers place the heating element perpendicular to the extrusion direction where in this case it was decided to place the heating elements in-line with the extrusion screw to maximize heat transfer from the heating element, to the heating block and to the extrusion barrel.

3.1.5 EXTRUSION BARREL

It was originally planned to use an existing v6 hot end available on E-bay for a few euros but due to situational circumstances a custom barrel was instead made. The heating barrel was instead machined on a lathe from a piece of round bar aluminum with a diameter of 30 mm to the desired size. The bottom end of the heating barrel was threaded to allow for a drilled out M10 bolt to be attached. The bolt held the heating block and bottom plate in place and pressed the whole assembly up towards the mounting bracket. The important measurements here were the diameters of the internal barrel as well as the diameter of the hole that would later become a female M10 thread.

Figure 18. Extruder barrel and V6 hot end

3.1.6 NOZZLE

The nozzle itself was mounted to a drilled out M10 hexagonal bolt. The bolt was placed in the lathe and drilled out until 6 mm was remaining in the bolt head. This was done to allow for a 5.4 mm hole to be drilled out from where a M6 thread could be made to take a standard 3D printer nozzle. Part of the thread of the bolt was stripped to allow for a prefect seal between the bolt itself and the bottom of the M10 thread inside the heating barrel. This is important as crevices may cause plastic to get stuck and introduce contamination to other plastics or get the extrusion screw itself stuck.

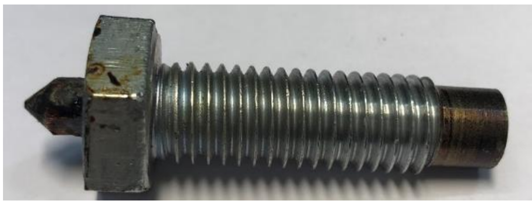


Figure 19. Drilled out bolt and nozzle

3.1.7 SCREW

The extrusion screw was an auger drill bit which was the ideal low-cost solution for a plastic extrusion screw. The drill bit was cut down to match the depth of the barrel and faced off in both ends to make them flat. In the top end a dent was made to allow for the tensioning screw (as mentioned in chapter 3.1.2 HOPPER and 3.1.8 TENSIONING PLATE) to line up properly and prevent the extrusion screw from rising during extrusion. Furthermore, the surface of the cutout area on the drill was smoothed out with sandpaper to decrease the friction between the polymer and the screw inside the barrel.

Figure 20. Auger drill bit with drive gear

Figure 21. Comparison of pre and post sanding of the screw

3.1.8 TENSIONING PLATE

As mentioned in chapter 3.1.2 HOPPER, another plate had to be made to put tension on the extrusion screw so that it didn't move up from the pressure of the molten plastic accumulating in the bottom of the barrel. The tensioning device was a M6 bolt that was conically ground down to a point to reduce friction between the contacting surfaces. The center hole was made to take an M6 thread and a nut was placed to allow for adjustment of the depth of the screw. The important measurements are the 31 mm c-c holes to fit the threaded rods as well as the centering of the screw hole.

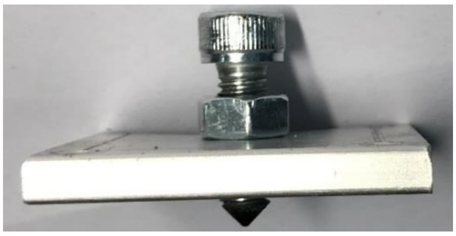


Figure 22. Tensioning plate and screw

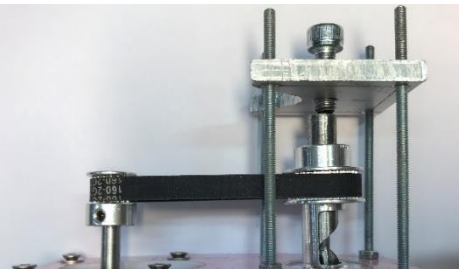


Figure 23. Tensioning plate mounted

3.1.9 ASSEMBLED EXTRUDER

The assembled extruder (minus motor wiring, thermistor, heating elements and cooling fan) is shown in *Figure 24. Assembled extruder*. The completely assembled and mounted extruder in action can be seen in *Figure 31. 3D Printing benchmark*.

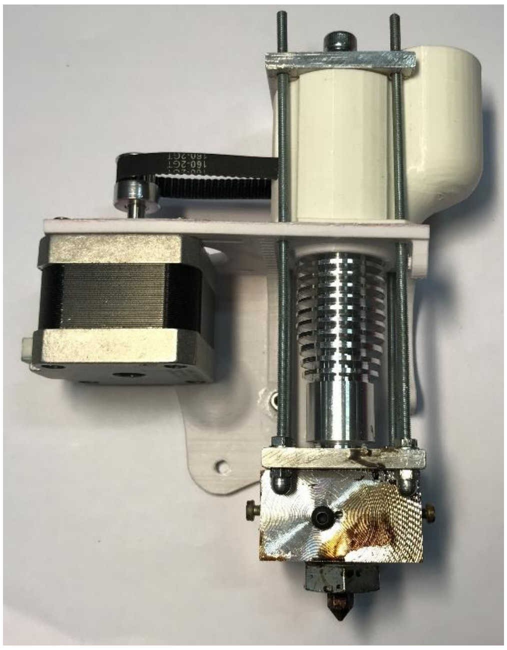


Figure 24. Assembled extruder

3.2 TESTING

3.2.1 HARDWARE

The first test that was conducted, as mentioned chapter 3.1.4 HEATING BLOCK, was the ability of the heating elements to reach required operating temperatures. A long temperature gauge was inserted in to the hole for the extrusion screw and the heating element was powered on. It was determined that a single heating element was not capable of efficiently reaching operating temperature so the decision was made to remake the heating block to hold two heating elements. The heating elements were both 12V 40W elements commonly used in 3D printers and each element manages at almost full power (12V, 3amp) to reach 147 degrees Celsius while mounted to this extruder. In “normal” 3D printers the attainable temperature with one of the same heating elements is commonly around 260 degrees Celsius.

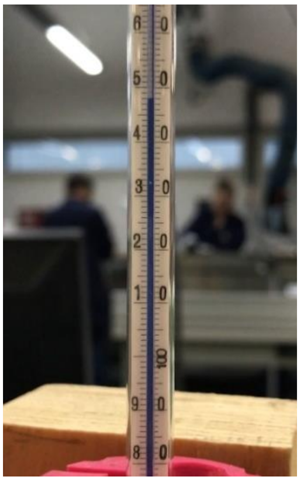


Figure 25. Heating test

A NEMA 17 stepper motor with a length of 34 mm (NEMA 17 stepper motors are identified by their length) was mounted to the extruder assembly and required a 4-pin cable connection to be controlled. A small box was 3D printed and since there were no available male connectors that fit the standard 3D printer cable safety pins were cut into 90-degree bends and glued to a piece of plastic. The 4 cables from a spare stepper motor cable were soldered on with 2 cables switching pins to complete the conversion that was necessary for driving the motor. The pins were insulated with silicone after the picture was taken.

Figure 26. Stepper motor cable conversion

With the heating and the motor under control it was tested if plastic could be transported through the extrusion barrel where it was noticed that regular size PP (Polypropylene) pellets were slightly too large for the (relatively) small 8 mm diameter extrusion screw to transport reliably through the heating barrel. Because of this it was decided to use extruded and reground PP material which had a smaller size granulates. The size of the pellets was however too inconsistent for reliable feeding.

A coffee grinder and a strainer were used in an attempt to make and separate smaller pellets. To an extend this worked however the grinder left a lot of larger pellets that weren't used. Greater success was had grinding down rafts and failed prints from the bin for (white) PLA trash. These parts nicely broke into smaller pieces that fit easily through the strainer. These pellets did not however exhibit good printing characteristics as they were 100% recycled.

Further inconsistency in feeding was fixed by increasing the voltage manually inside the 3D printer following a guide by Santiago (2019) allowing the motor to drive under heavier loads without releasing its holding torque. The voltage was increased from 0.765 Volts to 1.2 Volts. Important to remember when working with high current electricity is to be careful and methodical to prevent accidental shorting to ground or stabbing of the circuit board. With increased voltage comes increased temperatures. Safe operating temperatures for NEMA 17 stepper motors vary but are in general 50-70 degrees Celsius.

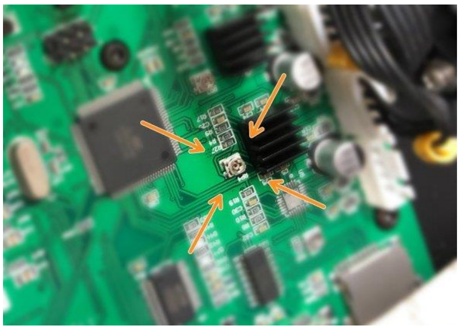


Figure 27. Stepper drive adjustment, (Santiago, 2019)

3.2.2 FLOWRATE AND SOFTWARE

As traditional 3D printers use a 1.75 mm (or 3 mm) diameter filament while printing a new printing profile (collection of settings) for the pellet fed extruder had to be made. The first step in this was figuring out the flowrate of the standard filament fed 3D printer. The flowrate calculation was done by taking a piece of plastic filament (in this case PLA) on to which a series of red dots in permanent marker was put. The filament was loaded in to a Creality Cr-10s since the pellet fed extruder is also designed for the same printer platform. The red marks on the filament were timed on how long it took for them to travel a known distance. This distance was selected to be the space between the Teflon feeding tube and the end of the inlet of the filament extruder assembly.

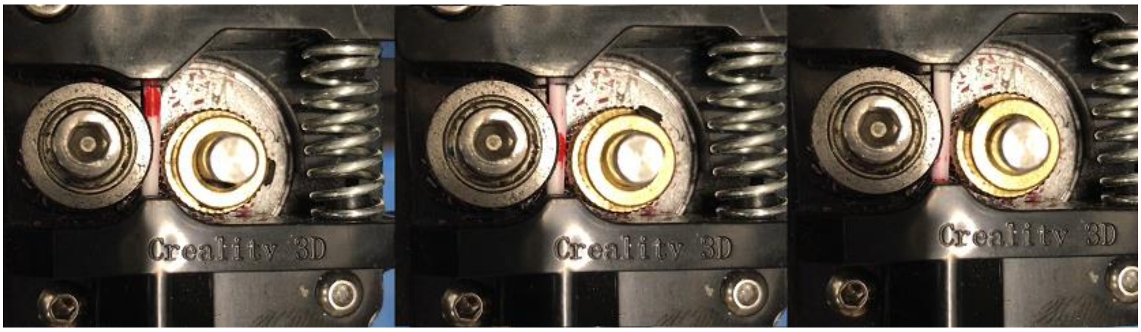


Figure 28. Flowrate measurement of filament extruder

The distance was calculated to be 11.1 mm and the time it took to travel that distance was calculated using camera frames recorded on an iPhone. With a framerate of 60 FPS (frames per second) one frame represents 0.01667 seconds. The number of frames from the red dot entering to its exit were calculated to be on average 1420 frames representing 23 seconds. The volume of the theoretical cylinder was calculated with the cross-sectional area of the filament multiplied by the distance (11.1 mm). This give 26.7 mm^3 volume over 23.667 seconds. The volume divided by the time gives the volume flowrate which was determined to be 1.128 mm^3 per second on average, at most 1.157 mm^3 per second at least 1.101 mm^3 per second.

Table 1. Filament extruder flowrate

parameter	value	unit	over	under	unit
print speed	20	mm/s			
filament d	1.75	mm	1.77	1.73	mm
cross section A	2.40528187	mm2	2.46057390	2.35061816	mm2
distance	11.1	mm	11.14	11.08	mm
frames	1420	frames	1421	1419	frames
60FPS	0.01666667	seconds per frame			
time	23.6666667	s	23.6833333	23.65	s
volume	26.69862882	mm3	27.4107933	26.0448492	mm3
volume flowrate	1.128111077	mm3/s	1.15738747	1.10126212	mm3/s
%			103 %	98 %	

The absolute maximum and absolute minimum flowrates were determined by assuming one frame more and one frame less for the time calculation as well as using the largest and the smallest diameters measured on the filament with calipers and a variation in the distance traveled. This was done to give a range of tolerable flowrates and a theoretical “optimal” flowrate.

PP granulate was used to calculated the melt flowrate ($^{mm^3}/_s$) of the extruder as it had good flow characteristics while being easy to process (as mentioned in the previous chapter). First plastic was extruded with the standard settings in Ultimaker Cura and resulted in a piece of plastic with a weight of 0,0067g divided by the melt density of PP gave a volume flowrate of 0.09875 $^{mm^3}/_s$ or roughly 9% of filament fed extruder’s flowrate.

The filament diameter in the settings was then changed to 1 mm and plastic was extruded with 13% of the original flowrate. This was repeated for a multitude of filament diameter settings and the closest flowrate was 28% at 0.25 mm filament diameter.

It was concluded that the easiest suggestion, to just change the diameter of the filament the printer thought it was using, was not suitable. The difference in time for the filament diameter test was due to the surrounding circumstances of the time of testing. The time should not significantly affect the flowrate since the plastic flow was consistent each test.

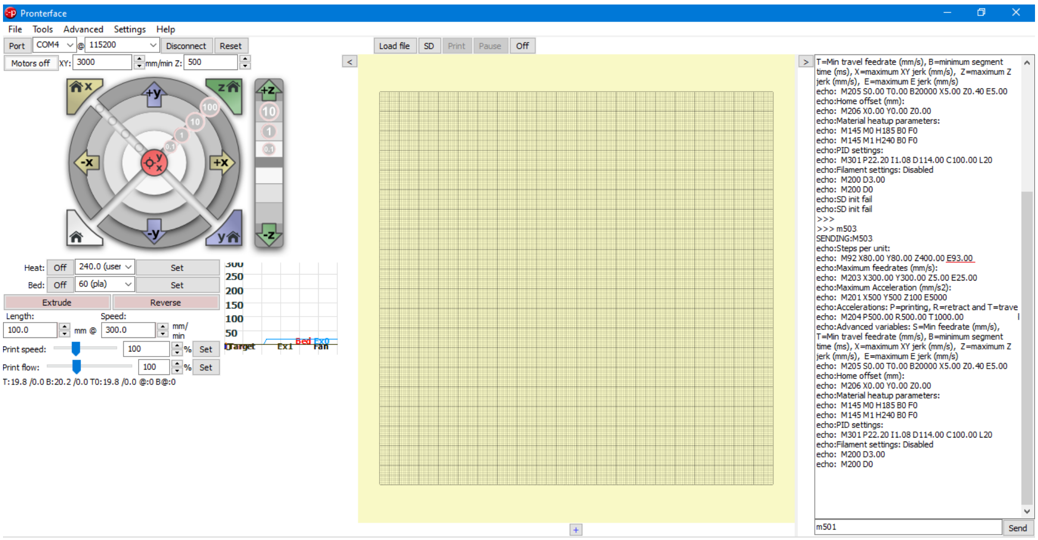
Table 2. Results from filament diameter testing in Cura

extruder	CR10s	Pellet Extruder theoretic filamentdiameter test						
filament d	1,75	1,75	1	0,5	0,25	0,125	0,625	mm
vol. fl. rat.	1,12811	0,09875	0,15227	0,20572	0,31597	0,12328	0,13432	mm3/s
time	23,6667	100	55	48	36	73	67	s
dist. (eq.)	11,1	11,1	11,1	11,1	11,1	11,1	11,1	mm
percentil	%	9%	13%	18%	28%	11%	12%	

For further testing the open source Pronterface software made under GNU General Public License was downloaded. Pronterface's easy to use interface and the ability to send individual g-code commands as well as loading pre-programmed g-code made it suitable for more in depth troubleshooting of the flowrate.

It was then considered to try to achieve the right flowrate by manipulating the g-code by inserting a flowrate multiplier M221 (Lahteine, 2020c). However, the flowrate multiplier is commonly used as a momentary adjustment to increase or decrease the flowrate of the plastic depending on the filament quality, print bed leveling and print settings or other factors at a specific point in time. (Hullette, 2019)

Using the M503 command a report of all current settings was posted in the console (Lahteine, 2020a) from where it was discovered that the standard setting for the extruder is 93 steps per 1 mm of filament.



Port: COM4 @ 115200
XY: 3000 mm/min Z: 500
Heat: Off 240.0 (user
Bed: Off 60 (pla)
Length: 100.0 mm @ Speed: 300.0 mm/min
Print speed: 100 %
Print flow: 100 %
T:19.8 /0.0 B:20.2 /0.0 T0:19.8 /0.0 @:0 B@:0

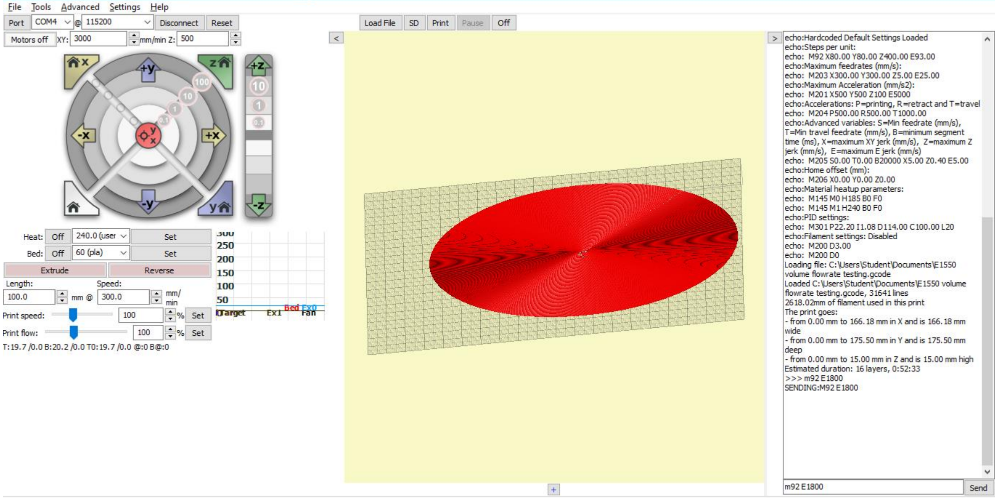
```
T=Min travel feedrate (mm/s), B=minimum segment
time (ms), X=maximum XY jerk (mm/s),  Z=maximum Z
jerk (mm/s),  E=maximum E jerk (mm/s)
echo:  M205 S0.00 T0.00 B20000 X5.00 Z0.40 E5.00
echo:Home offset (mm):
echo:  M206 X0.00 Y0.00 Z0.00
echo:Material heatup parameters:
echo:  M145 M0 H185 B0 F0
echo:  M145 M1 H240 B0 F0
echo:PID settings:
echo:  M301 P22.20 I1.08 D114.00 C100.00 L20
echo:Filament settings: Disabled
echo:  M200 D3.00
echo:  M200 D0
echo:SD init fail
echo:SD init fail
>>>
>>> m503
SENDING:M503
echo:Steps per unit:
echo:  M92 X80.00 Y80.00 Z400.00 E93.00
echo:Maximum feedrates (mm/s):
echo:  M203 X300.00 Y300.00 Z5.00 E25.00
echo:Maximum Acceleration (mm/s2):
echo:  M201 X500 Y500 Z100 E5000
echo:Accelerations: P=printing, R=retract and T=trave
echo:  M204 P500.00 R500.00 T1000.00
echo:Advanced variables: S=Min feedrate (mm/s),
T=Min travel feedrate (mm/s), B=minimum segment
time (ms), X=maximum XY jerk (mm/s),  Z=maximum Z
jerk (mm/s),  E=maximum E jerk (mm/s)
echo:  M205 S0.00 T0.00 B20000 X5.00 Z0.40 E5.00
echo:Home offset (mm):
echo:  M206 X0.00 Y0.00 Z0.00
echo:Material heatup parameters:
echo:  M145 M0 H185 B0 F0
echo:  M145 M1 H240 B0 F0
echo:PID settings:
echo:  M301 P22.20 I1.08 D114.00 C100.00 L20
echo:Filament settings: Disabled
echo:  M200 D3.00
echo:  M200 D0
```

```
m501
```

Figure 29. Pronterface and M503 report

The original settings were changed back to filament diameter 1.75 mm to minimize the change in the printer profile in Ultimaker Cura and instead redefine the steps the printer thought equals 1 mm of filament extruded. Since with the standard (1.75 mm) setting gave 7% of the intended flowrate the new steps per millimeter could be roughly determined by dividing 100 by 9 and then multiplying the new number by 93 steps $\left(\frac{100}{7}\right) \times 93 \approx 1033$ steps per 1 mm of extruded filament was the starting point for further testing.

The M92 g-code command was used to redefine the steps per 1mm for the extruder motor, M92 E1033 specifies the extruder motor to take 1033 steps per 1 mm (Lahteine, 2020b). A series of one-minute tests were performed where plastic was extruded for 1 minute straight from where the mass could be measured and divided by the melt density gave the volume which was then divided by time to give the melt flowrate $({mm^3}/_{s})$. The results were too inconsistent with the shorter flowrate tests but showed higher steps per mm was necessary. A longer test was designed to allow for plastic extrusion at a consistent pace for a longer time. Due to time constraints at the time of the testing only 5-minute tests were performed for a variation of steps per mm and only one test per step setting.



Port: COM4 @ 115200

XY: 3000 mm/min Z: 500

Heat: Off 240.0 (user Set

Bed: Off 60 (pla) Set

Length: 100.0 mm @ Speed: 300.0 mm/min

Print speed: 100 % Set

Print flow: 100 % Set

```
T:19.7 /0.0 B:20.2 /0.0 T0:19.7 /0.0 @:0 B@:0
```

```
echo:Hardcoded Default Settings Loaded
echo:Steps per unit:
echo:  M92 X80.00 Y80.00 Z400.00 E93.00
echo:Maximum feedrates (mm/s):
echo:  M203 X300.00 Y300.00 Z5.00 E25.00
echo:Maximum Acceleration (mm/s2):
echo:  M201 X500 Y500 Z100 E5000
echo:Accelerations: P=printing, R=retract and T=travel
echo:  M204 P500.00 R500.00 T1000.00
echo:Advanced variables: S=Min feedrate (mm/s),
T=Min travel feedrate (mm/s), B=minimum segment
time (ms), X=maximum XY jerk (mm/s),  Z=maximum Z
jerk (mm/s),  E=maximum E jerk (mm/s)
echo:  M205 S0.00 T0.00 B20000 X5.00 Z0.40 E5.00
echo:Home offset (mm):
echo:  M206 X0.00 Y0.00 Z0.00
echo:Material heatup parameters:
echo:  M145 M0 H185 B0 F0
echo:  M145 M1 H240 B0 F0
echo:PID settings:
echo:  M301 P22.20 I1.08 D114.00 C100.00 L20
echo:Filament settings: Disabled
echo:  M200 D3.00
echo:  M200 D0
Loading file: C:\Users\Student\Documents\E1550
volume flowrate testing.gcode
Loaded C:\Users\Student\Documents\E1550 volume
flowrate testing.gcode, 31641 lines
2618.02mm of filament used in this print
The print goes:
- from 0.00 mm to 166.18 mm in X and is 166.18 mm
wide
- from 0.00 mm to 175.50 mm in Y and is 175.50 mm
deep
- from 0.00 mm to 15.00 mm in Z and is 15.00 mm high
Estimated duration: 16 layers, 0:52:33
>>> m92 E1800
SENDING:M92 E1800
```

```
m92 E1800
```

Figure 30. Pronterface with 5-minute test

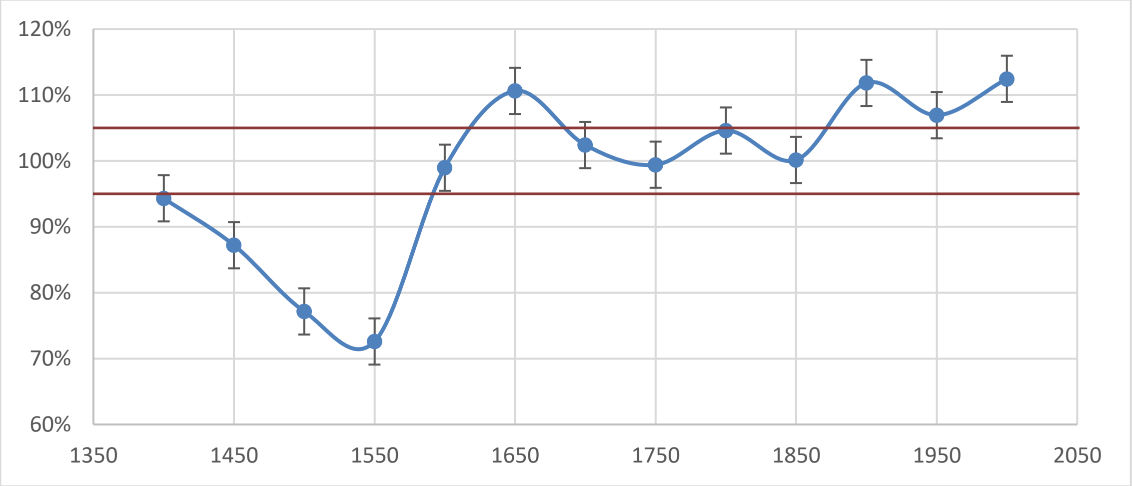
The five-minute test consisted of a one-layer spiral starting from the outside spiraling inwards with a constant print speed of 20 mm per second. The flow tests with different step settings were done so the change in steps per mm were never only increasing or decreasing, but constantly shifting to prevent potential pressure increase or decrease from increasing or decreasing the RPM as a consequence of steps per mm.

4 RESULTS

With a completed build and successful extrusion optimal extrusion speed was needed. This was to be found through volume flowrate testing and after a series of tests where plastic had been extruded at a constant velocity for a 5 minute period the results were in. The results for the 5-minute flowrate test shows some inconsistencies but show a general increase in flowrate with increased M92 E value. The outliers are 1450, 1500 and 1550 steps per millimeter.

Table 3. 5-minute test results

steps per mm	weight (g)	volume (mm3)	flowrate (mm3/s)
1400	0,2873	303,6997886	1,012332629
1450	0,2656	280,7610994	0,935870331
1500	0,235	248,4143763	0,828047921
1550	0,2211	233,7209302	0,779069767
1600	0,3014	318,6046512	1,062015504
1650	0,3369	356,1310782	1,187103594
1700	0,3119	329,7040169	1,09901339
1750	0,3028	320,0845666	1,066948555
1800	0,3186	336,7864693	1,122621564
1850	0,305	322,410148	1,074700493
1900	0,3406	360,0422833	1,200140944
1950	0,3257	344,2917548	1,147639183
2000	0,3425	362,05074	1,2068358



Graph 2. Results from 5-minute flowrate test

With a range of suitable M92E values an actual 3D model was attempted. The E value selected was 1800 steps per mm as it was in the middle of the range of theoretically suitable settings. The temperature was set to 230 degrees, (quite high for PLA) The benchmark chosen was the widely tried and tested “3D Benchy” (CreativeTools, 2015). The print failed roughly 10-20% through the way.

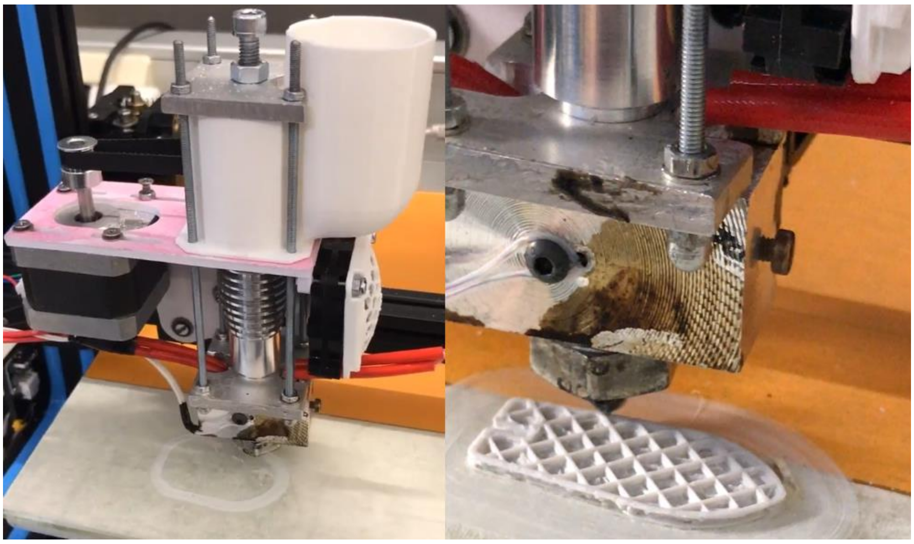


Figure 31. 3D Printing benchmark

5 DISCUSSION

The inconsistency in plastic flow may be because of the lack of pressure build up in the metering zone. This could be due to insufficient feeding of new granulate causing a pressure drop and could possibly be solved with using a smaller nozzle size, i.e. 0.3 or 0.2 mm rather than 0.4 mm. Reduction in the area of the opening increases the pressure inside. Having better granulate e.g. what would have been provided by Motoplast Oy had it not been for the corona outbreak, would also have helped with consistent feeding.

In regards to the actual print that was attempted the steps per mm were redefined mid print a couple of times to try to compensate when the flow of plastic was too high or too low. The first few layers suffered from elephant footing meaning there was too much plastic being extruded. The later infill layers were not receiving enough plastic and finally the volume flow was too low to continue printing.

Improvements that could be done are upgrading to a direct drive system and mounting it away from the extruder connecting the extrusion screw using a cable similar to that of older speedometer to lower the weight of the extruder and obtaining better control over the extrusion process itself, which is inherent with a direct drive as compared to a belt and gear drive. This would also allow for a better interface between the granulate and the extruder screw as well as room for an agitator to be mounted to keep the plastic in the hopper moving to prevent gaps in feeding. Finally the possibility of better extrusion if the screw does not enter the melting zone should be explored.

The build was sucessful but because of time constraints due to the corona outbreak further testing, troubleshooting and optimization was not possible. The larges current issue was the inconsistency in extrusion as well as access to finely ground plastic. Motoplast Oy had graciously offered to provide a hand full selection of half a kilo finely ground plastic pellets for testing but because of the closing of the campus on March 18th, 2020 this offer could not be pursued.

6 CONCLUSION

Plastic extrusion is widely used for different purposes, be that injection molding, additive manufacturing or general extrusion. To build a plastic extruder small enough to fit on a relatively small platform that is a 3D printer, one has to have imagination, practical problem solving abilities and a lot of patience. The analysis of the melt flow out of the printer gave a very warying result in all tests but the final and longest test gave what ought to be the most accurate representation of the melt volume flow at certain speeds. The results and variations are presented and potential solutions are suggested in the discussion.

This thesis documents the process of manufacturing the extruder, part by part, as well as (to an extent) what didn’t work. The testing and analysis of the extruder shows that with a redefinition of the printers own internal setting for what constitutes 1 mm of extruded filament adequate extrusion is possible. Moving from the original 93 steps (of the stepper motor) to something in the range of 1600-1900 steps is the indicated correct step count, according to the data at hand.

With proper granulate and more testing, optimal settings could be determined and a custom slicer profile could be created. This would likely bring up the printer to the quality and consistency equivalent to that of a traditional FDM (fused deposition modeling) 3D printer. For future progress and testing in the field of granulate fed extruders on 3D printers the manufacturing of, or access to, finer granulate is a must. Additionally, the screw design and the length of the screw extending in to the melting zone could be tested to see how the flow of plastic is affected.

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