Design and Development of a Small-Scale Pellet Extrusion System for 3D Printing Biopolymer Materials and Composites

by

Sean Matthew Whyman

Submitted to the School of Engineering and Advanced Technology
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Abstract

The aim of this research project is to develop a pellet-based 3D printing system that will accept biopolymer pellets to experiment with composite additives. Currently a majority of easily accessible or hobbyist 3D printers use filament as the input material for extrusion. With the goal in mind of printing using biopolymer materials and additive mixes, using filament remains achievable, but it would not provide as much freedom and exploration into unexplored areas. This can be an issue on the research side and a restriction on the hobbyist or consumer side where the material variety and printing capabilities such as recycling are much harder to achieve if not out of reach.

This research report presents the process of designing and developing a pellet-based extrusion system to accept a range of biopolymer pellets for 3D printing. The system has been designed from first principles and therefore can be extended to other materials with slight parameter adjustments or hardware modifications. A robust mechatronic design has been developed using an unconventional yet simplistic approach to achieve the desired operating characteristics. The extrusion system uses a series of control factors to generate a consistent output of material over the course of a print. The platform and surrounding processes are setup so that software can be used to define the printing parameters, thus allowing for easy and simple adaption to dissimilar materials. The utility of the extruder is demonstrated through extensive printing and testing of the printed parts.

Using Polylactic Acid (PLA) as the base material to test and develop the extruder system, the results of the print quality evolved as the extruders design became more robust. Several factors of the extruder contributed to large improvements such as; the hoppers rigidity, the internal geometries, the cooling efficiency and the software parameters. As these features progressed it enabled a much finer print quality and dimensional accuracy similar to what is seen in current Fused Deposition Modelling (FDM) extruders today. The print comparison tests were carried out against FDM

PLA samples to reveal a high similarity in mechanical strength and improvements to some areas of surface quality. Further testing revealed success in testing other materials such as PETG, as well as successfully mixing and extruding Harakeke flax fiber composite additives.

The major limiting factor of the current design is its ability to withstand heat propagation up through the extrusion system. As higher temperatures are required to melt different polymers, the thermal tolerance of the drive motor will quickly reduce causing inconsistencies earlier on during printing. The water cooling block added into the design only prevent heat from travelling through the wall of the extruder and not the screw. A further limitation is that the extruder is made using aluminium as the material. This allows for quick start-up times, but it also wears at a fast rate and the shaved off aluminium ends up contaminating the processed material.

Because this extruder accepts pellets, the range of possibilities for future applications is vast. With further improvements to better refine the process, the material range could expand to more unconventional materials that otherwise could not be printed using popular extrusion methods. As for a business sense, there are few well known methods of pellet printing and especially affordable systems. Therefore, an opportunity could be present to develop a commercially affordable desktop system or spin-off to enter a niche market.

Thesis Supervisors: Dr. Khalid Arif, A/Prof. Johan Potgieter

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Contents

1 Introduction **1**

2 Literature Review **4**

2.1 Types of Additive Manufacturing 4

2.1.1 Material Extrusion 7

2.1.2 VAT Photopolymerisation 8

2.1.3 Powder Bed Fusion 10

2.1.4 Direct Energy Deposition 11

2.1.5 Sheet Lamination 12

2.1.6 Material Jetting 13

2.2 Extrusion Printing Materials 14

2.2.1 Common Extrusion Materials 14

2.2.2 Extrusion of Biopolymer and Composite Materials 14

2.2.3 Recycling of Material 18

2.3 Current State of Extruder Technology 20

2.3.1 Deposit Extruder Types 21

2.3.2 Screw Extrusion 24

2.3.3 FDM Platform Designs 31

2.4 Summary of Findings 33

3 System Design **34**

3.1 Platform Design 35

3.2 Extruder System Design . . . 37
3.2.1 Material and Extrusion Type . . . 39
3.2.2 Hopper Design . . . 40
3.2.3 Proposed Extruder Design . . . 42

4 Development of Printer Systems **49**
4.1 Extruder Platform Development . . . 49
4.2 Extruder Design Process . . . 52
4.2.1 Hopper Development . . . 52
4.2.2 Cooling System Development . . . 59
4.2.3 Barrel, Screw and Die Development . . . 65
4.3 Measurement, Communication and Control . . . 70
4.4 Limitations and Improvements . . . 80

5 Mechanical Characterisation and Optimisation **81**
5.1 Print Consistency and Calibration . . . 81
5.2 Part Preparation . . . 91
5.3 Speed Versus Temperature . . . 94
5.4 Nozzle Sizes . . . 95

6 Results **97**
6.1 Printing Results . . . 97
6.2 Tensile Testing . . . 104
6.3 Recycling . . . 106
6.4 SEM Analysis . . . 108

7 Discussion and Conclusion **112**

8 Future Recommendations **114**

A Thermal Images **120**

B Publication **123**

C Conference Posters **125**

List of Figures

2-1 Melt extrusion additive manufacturing (FDM/FFF) [53] 8

2-2 Stereolithography (SLA) additive manufacturing [39] 9

2-3 (a) Inkjet powder bed printing (3DP), (b) Slective laser sintering (SLS) [39] 10

2-4 Laser operated DED process [34] 11

2-5 Sheet lamination additive process [36] 12

2-6 Material jetting process [35] 13

2-7 The Mark One 3D printer by MarkForged 17

2-8 Different extruder types; (a) Filament extrusion, (b) Syringe extrusion, (c) Screw extrusion [62] 20

2-9 Filament extrusion problems; (a) Filament is too thick, (b) Filament is too thin, (c) Filament buckling caused through the pressure being applied on the filament [62] . 22

2-10 Pellet extruder and positioning system [58] 24

2-11 Common single stage continuous screw extrusion system [27] 25

2-12 Single and twin screw extruders [55] 26

2-13 Screw mixing type comparison [33] 30

3-1 Pellet printing platform and extrusion system 35

3-2 Image showing the relative size and shape of the PLA pellets used in testing and composite blends 39

3-3 (Left) Assembled cross section view, (Rigth) Exploded cross section view 40

3-4 Images showing the dripfeeder with motor attached and the seperate guidance tube 41

3-5 (a) Common single compression or three stage continuous extrusion screw [47], (b) rubber extrusion screw [57], (c) wood auger drill bit 43

3-6 (a) Entire extruder system mounted in the printer, (b) full SolidWorks assembly of the extruder . . . 44
3-7 (Left) The Watlow 200W resistive heating band mounted at the extruders tip, (Right) Watlow PID single phase controller . . . 46
3-8 (Left) Coolant block around the neck of the extruder and the Teflon barrier, (Right) radiator, coolant reservior, pump and control temperature/feed controller to complet the loop . . . 47

4-1 (a) Flat sheet metal view of the frame design, (b) Folded sheet metal view with scale dimensions . . . 50
4-2 (a) Overview of the assembled model, (b) Close-up of the x/z axes custom joints and sliders, (c) Custom mounts for the y axis . . . 51
4-3 Drip feeder good and poor design considerations [57] . . . 52
4-4 (Left) SLS printed original hopper design, (Right) Solidworks model of the original hopper . . . 53
4-5 (Left) Flexing and deformation causes pellets to be force out, (Right) internal veiw of escaped pellets . . . 53
4-6 (Left) Sectioned view of new design in SolidWorks, (Right) Application of new hopper design . . . 54
4-7 (a) SolidWorks assembly of initial feeder design, (b) SLS printed initial feeder design 56
4-8 SolidWorks model of the new feeder design . . . 57
4-9 (Left) Feeder mount on top of extruder motor, (Middle) feeder friction fits inside mount, (Right) full feeder assembly with guidance tube into main hopper . . . 58
4-10 (a) Air cooled extruder with 40mm fan mounted, (b) SolidWorks model of the air-cooled extruder . . . 59
4-11 (a) First water cooled channel design, (b) SolidWorks model of initial water-cooled extruder . . . 60
4-12 Glycol based coolant temperature profile across several prints . . . 61
4-13 (a) Transient temperature study of the initial water-cooled block, stopped at 100°C in 180 seconds, (b) a static temperature analysis of the initial water-cooled block . . . 62
4-14 (a) Transient temperature study of the new water-cooled block, stopped at 100°C in 260 seconds, (b) a static temperature analysis of the new water-cooled block . . . 62

4-15 (a) PTFE thermal barrier water cooler, (b) SolidWorks model of the PTFE water cooled design . . . 63
4-16 Water based coolant temperature profile across several prints . . . 64
4-17 Visual pressure comparison between a multi-zone continuous screw and the no compression auger screw [14] . . . 66
4-18 Screw geometries [57] . . . 67
4-19 (Top) Isolated melt region with correct feed transport, (Bottom) Block occurred mid way down . . . 68
4-20 (a) Initial air-cooled extruder design, (b) first water-cooled extruder design, (c) latest water-cooled extruder design with a thermal barrier . . . 69
4-21 Extruder system process . . . 71
4-22 Extruder sensor and monitoring locations . . . 72
4-23 Control interface for the temperature and feeder access . . . 74
4-24 (Left) Eagle designed controller schematic, (Middle) top view of controller containing the interfaced electronics, (Right) underside of board showing the deliberate jumper wires . . . 74
4-25 Main controller loop running based on a timer counting routine . . . 75
4-26 Serial reading function within the loop to detect incoming instructions . . . 76
4-27 Feeder speed function and drive motor encoder interrupt function . . . 77
4-28 Feeder enable/disable function and the feeders reverse function . . . 78
4-29 Temperature calculation function using an open source library . . . 79

5-1 First test print attempt carried out using a PLA and flax fiber blend . . . 82
5-2 (Left) Increments in layer thickness, (Right) Refined parameters . . . 82
5-3 (Top) Single layer test print for settings, (Bottom) Full print with adjusted parameters and skirt . . . 85
5-4 Continued testing from the early fiber blend to just PLA . . . 86
5-5 1.5mm aerated PLA extrudate . . . 86
5-6 (Left) High moisture content, (Middle) Insufficient material feed, (Right) Overheated material . . . 87
5-7 Test printed 40% infill part with collapsed bridging on top layer . . . 87

5-8 (Left) Stuttering drive motor caused oozing around the perimeter, (Right) Oozing between movements across the part . . . 88

5-9 This is a set of g-code instructions written to extrude and wipe the nozzle before the print begins . . . 89

5-10 (Left) Excessive heat build-up caused runny viscosity, (Right) Insufficient layer cooling as the layer size reduced . . . 89

5-11 (Left) - (Middle) Visible build-up and mixing of aluminium contamination, (Right) Unmixed aluminium powder caused through rubbing . . . 90

5-12 Visual representation of the slicing operation carried out in Slic3r . . . 91

5-13 Pronterface as the graphical interface for the printer . . . 92

5-14 Basic considerations of die design [57] . . . 96

5-15 The different sizes and types of extrusion tips used (2.0, 1.5, 1.2, 1.0, 0.8, 0.6mm) . . . 96

6-1 Air-cooled extruder progress from the first print through to a more optimised result 98

6-2 (Top) Glycol-cooled extruder trialling parameters, (Bottom) More refined print settings 99

6-3 Comparison of print quality (Left) First water-cooled extruder, (Right) Refined Teflon water-cooled design . . . 99

6-4 (a) Printed a large trophie mount with an internal magnet and 40% infill, (b) Tall thin-wall pencil holder, (c) A printed part comparing black ABS filament and PLA pellet, (d) Assortment of finished prints . . . 100

6-5 PET printed sample . . . 101

6-6 Printing samples using a Harakeke Flax Fiber and PLA composite blend; (a) Completed composite sample, (b) First attempt with new blend producing a light colour, (c) Second attempt with heating causing a dark colour, (d) Image taken during the print, (e) Extruding a bead of the composite material . . . 102

6-7 The variety of polymers tested in this extruder with a 1.5mm nozzle, (Left two) Harakeke Flax PLA composite, (Middle) PET, (Right two) PLA . . . 103

6-8 Instron tensile tester demonstrating the gripped specimen and extensometer . . . 104

6-9 Box and whisker graph comparatively showing the tensile strength of each sample set 106

6-10 Tensile test results for four sample groups as per Table 6.1 . . . 107

6-11 (Left) SEM result showing the layer bonding and bead shape, (Right) Close up of the voids that occur between roads . . . 109

6-12 SEM results (Left) white PLA at 190°C, (Right) Natural PLA at 190°C [64] 109

6-13 SEM surface of pellet sample (Left) Showing upper surface edge, (Right) Showing lower surface edge 110

6-14 SEM surface of filament sample (Left) Showing upper surface edge, (Right) Showing lower surface edge 111

6-15 (Left) Showing central pellet sample surface, (Right) Showing central filament sample surface 111

List of Tables

2.1 Printer categories and types 6

2.2 Bio-degradable materials for 3D printing [54] 15

2.3 Natural Fibers in the world and their world production [30] 16

2.4 Specimen tensile testing properties [54] 18

2.5 Classification of polymer extruders [57] 25

2.6 Comparison of Dispersive Mixers for Single Screw Extrusion [57] 30

3.1 Styles of different printer platforms, outlining design positives and negatives 36

3.2 Types of extruder used in extrusion 3D printing, outlining positives and negatives . 37

4.1 Extrusion screw properties based on the proposed extruder 69

4.2 Common RepRap printing g-code commands [6] 71

5.1 Different printing parameters between materials to achieve accetable results 83

5.2 These are some of the common printer settings accessed in Slic3r and used to manipulate the printing characteristics 84

5.3 Extruder Barrel Type; Printer Conditions, (a) Full aluminium water cooled block, (b) Aluminium PTFE thermal barrier water cooled block 94

6.1 (a) For parts printed without PTFE thermal barrier, liquid cooling and 1.5 mm nozzle, (b) same as (a) with PTFE thermal barrier, (c) same as (b) with 0.8 mm nozzle, and (d) same as (c) but printed at a higher speed. 105

Chapter 1

Introduction

This research is aimed at accurately and consistently 3D printing biopolymer and composite materials through a pellet extrusion system. The presented literature outlines the current Additive Manufacturing (AM) areas and focuses on finding the most appropriate means of processing pellet materials. The research focus narrows down to extrusion deposition printing methods as other systems that support powders or resins are restricted around material choice, particularly biopolymers and composites. Because the proposed objective requires processing of pellets and appropriate composite mixing capabilities, the choice of extrusion system was reduced to screw-based extrusion. Due to the few options for pellet extrusion printing available for purchase or within a reasonable price range, the design of a complete extruder and printing platform is necessary to carry out the desired testing. Therefore, a custom system design and development has been detailed in this report to enable the processing of biopolymer pellets and composite materials such as biopolymers infused with Harakeke flax fibres.

For the purpose of research, usability and to keep the price reasonable, the platform size is chosen to have a small build volume to match current small scale FDM printers already available. The polymer screw extruder is largely based off standard single screw extruder designs, but due to the size of this system, modifications are needed to raise the performance so that it acts more like a 3D printer. For this to be practical, the extruder needs to be compact enough for it to be usable on a small platform, but also powerful enough to perform like an extruder. The development focus of the extruder is not only to extrude the intended polymer, but to do it with consistency and reliability over longer periods of time. The extruder was designed to closely resemble a rubber extrusion process where the screws material progression is focused more on transporting the polymer and pumping it out. Because this is to be a small system, along with the method of heating, the efficiency of cooling will also play a large part in keeping the consistency.

The problem with developing a small screw extruder is first finding out if this is a feasible objective. The pellet extruder printers available are still quite large and some papers outline that shrinking a screw using scaling rules eventually reaches a point where it becomes impractical. Therefore, the first step in this research objective is to find out if the theoretical design will work before refining it. If this proves positive, the following question is, how does this technology compare to its filament printing counterpart. Lastly the printer needs to be able to answer the question, can it mix and print additives such as Harakeke flax fiber to create a biopolymer composite.

To achieve these questions the project objectives are as follows:

- Design a Cartesian platform to support a screw extruder. The platform needs to have the appropriate accuracy for 3D printing, similar to current printers which are already available (approximately 0.1mm of accuracy). It also needs to accommodate the size and weight of the extruder, as well as any potential changes that could occur. Because this platform will be designed for a nonstandard form of extrusion, the choice of hardware/software needs to not only be compatible, but also heavily configurable.

- Develop a single screw extruder to accept and extrude the biopolymer pellets provided by Scion New Zealand. The pellets are a cylindrical shape and the random dimensions range from 1 to 3mm in both length and diameter. This part can be broken down into several steps:
  - Development of a hopper for guiding the pellets into the screw and a drip/starve feeder to control the feed quantity of material entering the extruder.
  - A screw, barrel and die for transport of the polymer into the heated region and out of the extruder.
  - A means of heating the polymer to generate a melt zone and a system to efficiently cool/contain the heat from expanding beyond the heated region.

- Development of a control/feedback system for the drip-feeding mechanism and the cooling system. This is to monitor and collect data on the cooling efficiency to see if there is a relationship between the barrel temperature and the mechanical characteristics.

- Test the functional design to see if it can operate sufficiently as a printer. This can be evaluated by testing its dimensional accuracy of the output objects in comparison to the 3D model. Also, the mechanical and visual aspects of the output can be compared against other FDM printers using similar material.

The polymer used in the initial testing and development phase is polylactic acid (PLA). This platform is designed to accept a wide range of pelletised polymers including some experimental ones. Prints will be carried out and tested to determine the tensile strength of the welded layers of the samples. A Scanning Electron Microscope (SEM) can be use to identify flaws in the printed parts for analysis and comparison. Further changes will be added to the system to improve the cooling, feeding and control characteristics to further improve the quality and consistency of the output.

Chapter 2

Literature Review

The literature presented in this chapter shows findings around a broad spectrum of additive manufacturing technologies found in the current marketplace. The focus of this review is to discover the best method of extruding biopolymer materials and composites with a consumer approach towards 3D printing. This research considers the advancements around 3D printing technologies, how they work, which materials they work with, and their ability to provide the most flexible option. Finally, it narrows towards which processes suit our needs and looks at the state of the technology around our chosen process.

2.1 Types of Additive Manufacturing

Additive Manufacturing (AM) or 3D printing is a rapidly growing technology that allows both testing and production of three dimensional objects with complex geometries. The beginning of 3D printing came about with the invention of Stereolithography (SLA) in the 1980's by Charles Hull [40]. Because this was created not long after the inkjet printer in the 70's, leading to thinking it may have played a part in its development. Soon after SLA, the invention of Fused Deposition Modelling (FDM) printing by S. Scott Crump [25]. The direction of these devices shifted from the idea of being a rapid prototyping tool to an actual manufacturing device used for fabrication and development purposes. The advancements in technology over the next few years began to step towards more functional purposes with contributions to many different areas, one area of greater impact is in medical applications. Some of these applications include using printing to produce porous scaffolding to aid in tissue regeneration, the movement towards printing working organs, prosthetic development and visual aids for parts of the human anatomy [39]. Some other areas of development include expansion in the open-source hobbyist area, automation, artistry, medicine and research [22, 59, 66]. Currently additive manufacturing has a large community behind it and a wide range of printer types with varying degrees of accuracy to created parts with specific dimensional, mechanical and aesthetic properties [12].

Subtractive manufacturing is the process by which material is cut away/removed using machinery such as a mill or lathe to reveal the object. The opposite of this is Additive Manufacturing, which involves an accurate bonding of deposited material inside a two-dimensional x-y plane. With the addition of a z axis, the material planes stack up and add together to form a three-dimensional object. An advantage of AM processes is a significant reduction in waste material, often reducing the need to recycle and can be explored as a potential manufacturing business advantage [22]. Additionally, with the lack of high speed cutting bits in AM processes, the result is minimal component or tool wear, thus less maintenance and down time. Some complex parts if done using subtractive methods could require multiple machining processes or an expensive multi-axis machine to produce as opposed to generating support material when printing. Certain AM process can also have greater control over material properties through for example, mixing in additive materials or through process manipulation. This could be done through directing the deposited material during printing as to increase strength about a desired axis, or by changing the material composition through material additives such as fiber reinforcement [13, 28, 29, 46].

As additive manufacturing has evolved, new methods of 3D printing have been developed allowing for a much wider range of material choices, printing accuracy and variety in application. Table 2.1 shows the different AM categories each with a range of process techniques.

Table 2.1: Printer categories and types

PRINTER CATEGORIES	PRINTER TYPE
Material Extrusion	Fused Deposition Modelling (FDM)
	Fused Filament Fabrication (FFF)
	Melt Extrusion Manufacturing (MEM)
	Plastic Jet Printing (PJP)
	Fused Filament Modelling (FFM)
VAT Photopolymerisation	Stereolithography (SLA)
	Digital Light Processing (DLP)
	Scan, Spin, Selectively Photocure (3SP)
	Continuous Liquid Interface Production (CLIP)
Powder Bed Fusion (FBF)	Selective Laser Sintering (SLS)
	Selective Heat Sintering (SHS)
	Direct Metal Laser Sintering (DMLS)
	Electron Beam Melting (EBM)
	Selective Laser Melting (SLM)
	Multi-Jet Fusion (MJF)
	Inkjet 3D Printing/Plotting (3DP)
Direct Energy Deposition (DED)	Laser Based Metal Deposition (LBMD or LMD)
	Direct Metal Deposition (DMD)
	Direct Light Fabrication (DLF)
	Laser Engineered Net Shaping (LENS)
	Laser Freeform Fabrication (LFF)
Sheet Lamination	Ultrasonic Additive Manufacturing (UAM)
	Laminated Object Manufacturing (LOM)
	Selective Deposition Lamination (SDL)
Material Jetting	Smooth Curvatures Printing (SCP)
	Multi-Jet Modelling (MJM)

2.1.1 Material Extrusion

Out of all of the different AM categories, some of the most well-known methods of printing are part of the material extrusion process category. These come under various names which essentially mean the same thing. The most common name recognised is Fused Deposition Modelling (FDM) brought about and trademarked by Stratasys, Inc, however a more generalised name is Fused Filament Fabrication (FFF). Thermoplastics are typically the material of choice in this process. The materials commonly seen are Acrylonitrile Butane Styrene (ABS) and Polylactic Acid (PLA).

FDM printers are not confined just to using polymers. Other forms of extrusion such as a syringe extruder can use materials which do not require heating to reach a liquid form. An example is using different types of food or biological samples [56]. The melt extrusion process works by heating up material to its molten state and pressing it out of an extrusion tip to form a bead, the bead of material is then deposited onto a heated platform (Fig. 2-1). Throughout the printing procedure, control of the temperatures, feed-rate and extrusion rates are implemented to maintain accuracy and create 2D layers which are built up to form a 3D object [28].

In comparison to other methods of printing, extrusion is not of a high accuracy. Typically, extrusion thicknesses range between 0.1-1.2mm and large variances can depend on the material used, the nozzle size and the printing orientation. The post processing for these printers is very minimal, at most a secondary extruder may be used with dissolvable material, but more commonly removable support material is generated through slicing software that can be pulled off by hand or using basic tools such as pliers. Due to the varied accuracy of these printers, noticeable step formations are caused through the layering process and artefacts are left on the surface. Although this is not always a problem and is more prominent in complex geometries, depending on the material used this can be reduced by using techniques such as sanding or methods of vaporising [50].

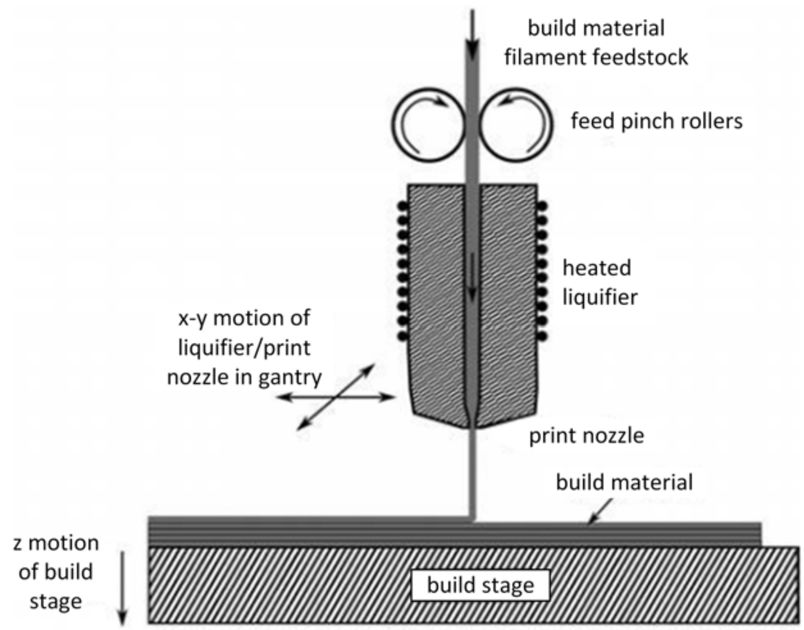


Figure 2-1: Melt extrusion additive manufacturing (FDM/FFF) [53]

2.1.2 VAT Photopolymerisation

VAT Photopolymerisation is the first type of 3D printer technology to come about in the form of Stereolithography (SLA) developed by 3D Systems, Inc [66]. It does not heat or feed material like extrusion processes, instead it works using an ultraviolet (UV) light or a laser source and requires a photopolymer (liquid resin) as the medium from which a part is created. The resin is held inside of a vat or tank that the build platform is either lowered into, or raised out of exposing the next layer. In terms of an SLA printer, an ultraviolet laser is used with a 2D galvanometer (galvo) scanning mechanism to direct the beam across the layer and cure the resin in the shape of the part as seen in Fig. 2-2. An LCD printer uses pixels to direct light onto specific spots of a layer. This is done by turning individual pixels on and off to provide openings for light to pass through and cure the resin. Similar to method of an LCD printer, a DLP printer uses a projector to display an image onto each layer.

Unlike laser scanning which targets individual points at any given time, an LCD/DLP printer can expose light to an entire layer all at once, making for a quicker process. The downside for both LCD and DLP printing is that the resolution is limited by the physical pixel size. Whereas the laser scanning mechanism generates a much smoother line and surface finish. In comparison to extrusion printers the accuracy and resolution is much greater with a resolution of about 0.03-0.1mm and less than 10μm in microstereolithography. The post processing is however more involved. Some prints can require post curing of the part to obtain strength and the support material can require a

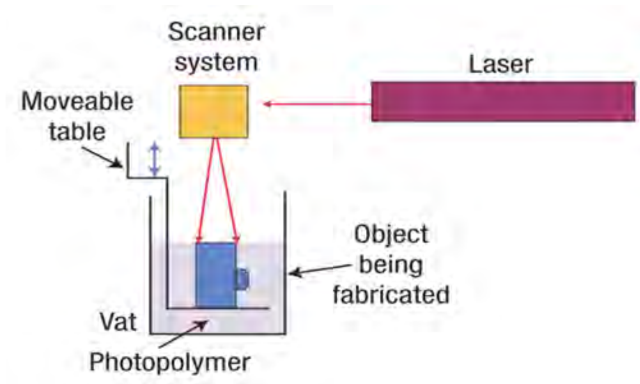


Figure 2-2: Stereolithography (SLA) additive manufacturing [39]

separate chemical process to remove.

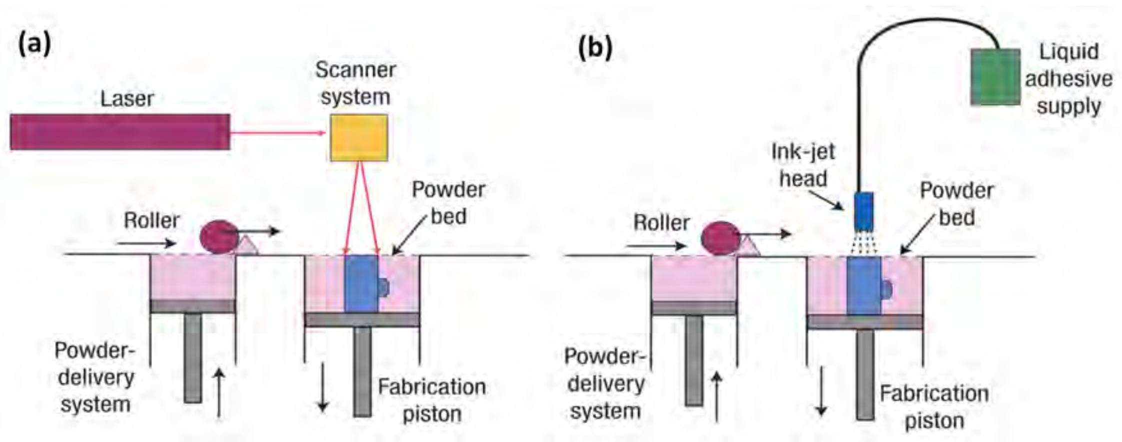


Figure 2-3: (a) Inkjet powder bed printing (3DP), (b) Slective laser sintering (SLS) [39]

2.1.3 Powder Bed Fusion

Powder Bed Fusion (PBF) has processes very similar to an SLA printer, however instead of using resin as the medium, an object is created by fusing powdered material together using techniques such as laser or electron beam sintering and ink-jet adhesion (Fig. 2-3). The fine powdered material is held in a tank, during printing the build platform is lowered for each layer and the material from the tank is spread over the build platform to create each successive layer (Fig. 2-3). Any excess powder falls into overflow catchments for re-using. In order for the material to sinter, the chamber is heated to within a few degrees of the material's melting temperature. For an SLS printer, a laser galvo scanning mechanism directs the beam over the powdered layer. The powder absorbs the localised energy spectrum of the laser to raise the material's surface to its fusion point, bonding the material particles together. For other processes such as Electron Beam Melting (EBM), a high voltage electron laser beam is used inside of a vacuum chamber to melt the material particles [66].

The accuracy of an SLS-like device is limited by the particle sizes. The typical accuracy is around 0.1mm which is comparable to current FDM techniques, although these devices can produce parts with greater complexity. An issue with this technology is the sintering density; if the density of a large object is too high, the absorbed heat can build up around the part causing unwanted particles to transition into a molten state and fuse. An advantage of this technology is that it offers a greater selection of material combinations including metals or the ability to use technologies such as Inkjet 3D Plotting (3DP) with natural materials for use in medical applications [20]. Post-processing is required for these printers to clean up any support material, excess powder and porus surfaces. Some machines, such as a Selective Laser Melting (SLM) printer, may require inert gas environments for health and safety reasons. This can be a very costly addition as powders such as Titanium are highly flammable and require specialty devices to handle.

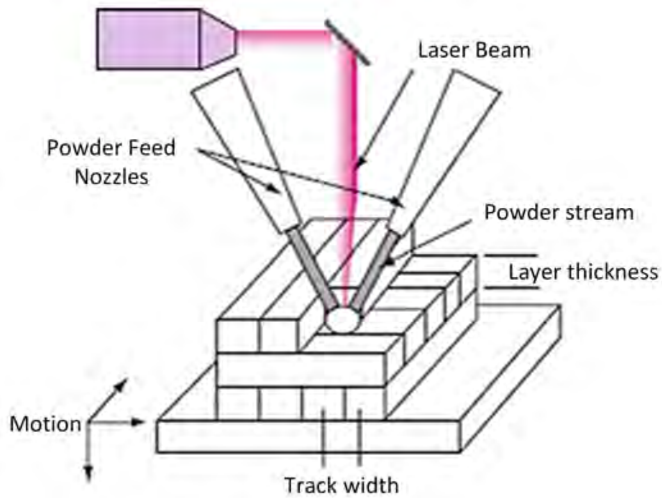


Figure 2-4: Laser operated DED process [34]

2.1.4 Direct Energy Deposition

Gibson [34] defines Direct Energy Deposition (DED) not as one single method of printing, as they are quite often sold as flexible platforms for calibration depending on the process and material. These processes can be thought of as being similar to welding, but instead of forming a melt pool through high current and contact, the melt is formed via a laser or electron beam with the melt occurring on or before reaching the contact surface as seen in Fig. 2-4. These processes use a delivery nozzle to direct metal powder or filament (wire) onto a bed or part directly.

Processes such as Laser Bed Melt Deposition (LBMD) are very similar to the powder bed fusion techniques previously discussed, except a nozzle is used to deposit material. The powder-based approach is not as efficient as using wire, this is due to the way in which the material is applied. In terms of powder, the material deposited is more likely to spread out to the point where the melt pool from the energy beam does not use all of the material. This is not the case when using a wire fed system where the material deposit is fixed and consistent. LBMD systems can achieve pool accuracies of around 0.25-1mm in diameter and 0.1-0.5mm in depth. These systems do not necessarily generate the best resolution and have a poor surface finish which may require manual labour to clean. Some of these processes may need the use of inert environments for health and safety purposes; some powdered materials are highly flammable. DED processes are also capable of repairing damaged parts by building up the surface area.

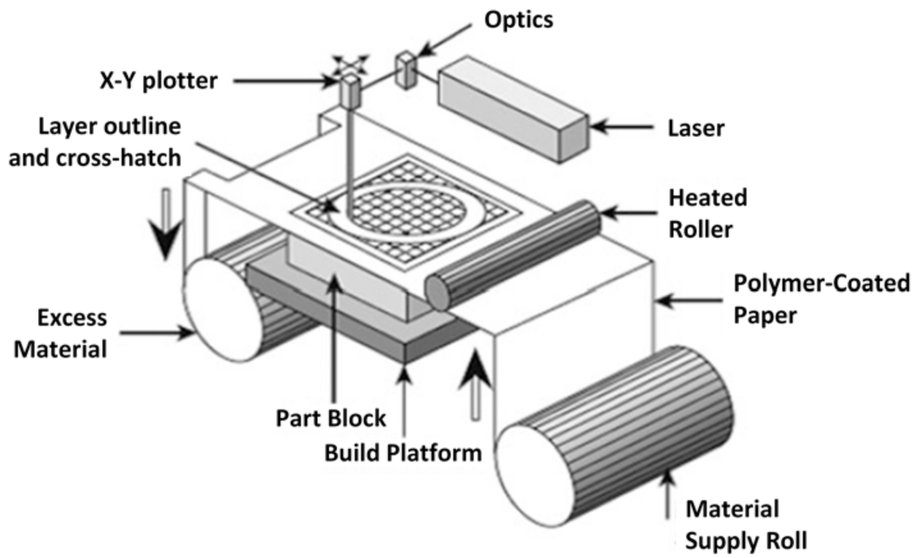


Figure 2-5: Sheet lamination additive process [36]

2.1.5 Sheet Lamination

Sheet Lamination involves the bonding of sheets as the method of layering, where the sheets are either stacked or cut from a role of material. A sheet of material is placed over another and bonded using some type of adhesive technique either before or after being cut into shape using a CO_2 laser/blade (Fig. 2-5). In the form of Ultrasonic Additive Manufacturing (UAM), ultrasonic welding is used as the form of adhesion between layers [66]. Post processing can be carried out to refine the object to fit the desired shape, but it is not necessary. The layer accuracy of this process is dependent on the sheet thickness and the strength of the part is defined by the method and strength of the adhesive. UAM is able to use different materials such as metals or plastics with the ability to weld them together, Laminated Object Manufacturing (LOM) is able to use additional materials such as paper, films and metal foil [56]. The accuracy of these printers is determined by the accuracy of the cutting and the thickness of the layered material.

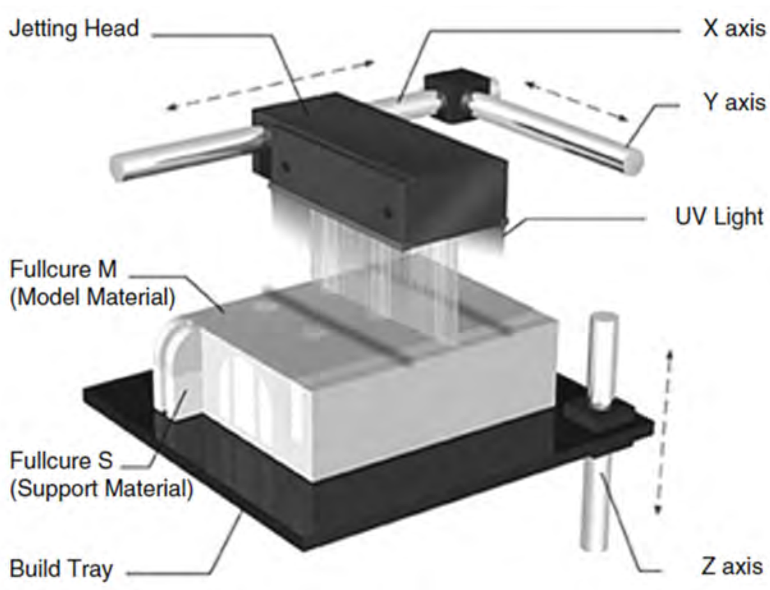


Figure 2-6: Material jetting process [35]

2.1.6 Material Jetting

Material Jetting is a very accurate process and quite similar to the methods of inkjet 3D printing using powder. The jetting systems started off as wax based printers and have shifted towards liquid thermoplastics and lately photopolymers. One method of jetting is to use a Continuous Stream (CS). This works by applying continuous pressure to a liquid with low viscosity, causing it to jet out of an oscillating nozzle in the form of a column that breaks up into droplets (Fig. 2-6). The frequency of oscillation determines the droplet formation and can be controlled on ejection. The other method is to use a Drop on Demand (DOD) technique where material is pulsed out of a nozzle when needed.

One method of doing this is to use piezoelectric actuators to push out a droplet. Another more uncommon example would be an optimized micropipette system used in a 3D Systems printer [35]. Heated materials cool as the method of curing, whereas photopolymers are cured through ultraviolet light (UV). This method of printing is limited by the viscosity of materials thus heavily limits the choices in materials. DOD accuracies can be as low as 13μm making for a very fine print, but the build time becomes very long. These processes often require post-processing using chemicals to remove wax-like support materials.

2.2 Extrusion Printing Materials

2.2.1 Common Extrusion Materials

FDM or extrusion-based systems are some of the more flexible, simple and supported ways of 3D printing a variety of materials. Currently FDM printers are some of the most common build-and-test platforms offering a narrow variety of polymers to choose from and slowly making progress towards the increased use of biopolymer materials. Although this form of additive manufacturing can produce complex parts, it still has a limited variety of material selection in comparison to injection moulding. It is the first choice for enthusiasts and is often used as a development platform to conduct experiments around additives and material reinforcement.

Each material used in FDM printing needs to meet the correct criteria for extrusion to run smoothly. The melting point and viscosity needs to be low for the polymer to flow correctly and bond sufficiently when deposited [54]. One of the most popular filament materials used in FDM 3D printing is Acrylonitrile Butane Styrene (ABS). It has strong mechanical properties and it comes in a variety of colours, but it has poor weather resistance. An alternative filament material is Polylactic Acid (PLA) made from renewable resources such as sugars and starches. Other common types of printing materials include Polyethylene Terephthalate (PET/PETG), Nylon, Thermoplastic Elastomer/Polyurethane, Polycarbonate, Polypropylene and High-Density Polyethylene. More interesting composite filaments are also available, such as wood and metal but these do not necessarily offer a mechanical advantage rather they are chosen for their aesthetic look and feel [54].

2.2.2 Extrusion of Biopolymer and Composite Materials

As previously mentioned, each polymer needs to melt at reasonably low temperatures and when melted they need to have a low viscosity. PLA provides comparable strength characteristics to the popular material ABS and it is formed using natural starches and sugars meaning it is biodegradable. Recent advancements have seen biomaterial printing of natural and synthetic 3D scaffolds to support tissue growth in medical applications using stem cells. Biomaterial printing methods and devices have been outlined in Chias work [20] with a large focus on the materials, as well as the advantages and disadvantages of each printing process. The research brings to light the popularity of FDM devices with its low-cost benefits, different biocompatible polymers and material limitations around thermoplastics. SLA is one such viable solution, however the lack of material choice is a limitation of this application, thus there is needed development surrounding biomaterials.

Table 2.2: Bio-degradable materials for 3D printing [54]

Material	Produced From	Properties	Extrusion Temp. ($^{\circ}$C)	Pros.	Cons.
PLA	Plants Starch	Tough, Strong	160 - 222	Bio-plastic, non-toxic, odourless, low-warp	Low heat resistance, brittle
PVA	Petroleum	Water-soluble, good barrier	190 - 210	Biodegradable, recyclable, non-toxic	Expensive, deteriorates with moisture, special storage
PHA	Sugars with biosynthesis	Several copolymers, brittle and stiff	160	UV-stable, stiffness	Elasticity, brittle
HIPS	Petroleum	High impact resistance, soluble in limonene	190 - 210	Biodegradable, low cost, similar to ABS	Warping, heated printing bed
PET	Petroleum	Strong and Flexible	210 - 230	FDA approved, Recyclable	Absorbs moistness

The current thermoplastic materials available on the market provide a limited range of properties for selection, with a focus on mechanical strength. Thermoplastic polymers are single or two dimensional molecular structures able to soften at higher temperatures and regain their properties as they cool down [51]. Although the properties of current filament printing materials, such as ABS, are desirable amongst enthusiasts, what is not considered is the reuse or impact of the waste material produced. Biodegradable polymer options are slowly becoming known with options like PLA and Polyethylene Terephthalate (PET) as seen in Table 2.2. These polymers not only have similar or better strength performance characteristics compared to common polymers such as ABS, but they are more sustainable with their low cost, biodegradability and production from renewable resources [54].

Even with the increasing variety in material choices, there is still no comparison with injection moulding. There are many material advancements with the inclusion of additives and fillers to modify or improve material properties, but a lot of these are still in the thermoplastic category [20]. Other options currently available for FDM systems include the use of fillers, either fiber or particle based. Research has been conducted around composite fiber reinforced materials as they offer a lower cost alternative with strong mechanical properties and some possess bio-degradable eco-friendly features [42].

Some common synthetic or petroleum-based polymers used are ABS and nylon with printers already produced with the ability to print them using fiber as a reinforcement. Although synthetic fiber reinforcement has not been around for long, studies and testing has already been conducted on the tensile properties of natural fibers as a means of replacing synthetics [42]. Mohammed [51]

Table 2.3: Natural Fibers in the world and their world production [30]

Fiber Source	World Production (10^3 ton)	Tensile Strength (MPa)
Bamboo	30000	140 - 230
Sugar Cane	75000	-
Jute	2300	393 - 773
Kenaf	970	930
Flax	830	345 - 1035
Grass	700	-
Sisal	375	511 - 635
Hemp	214	690
Coir	100	175
Ramie	100	560
Abaca	70	400

outlines the production quantities and properties of common natural fibers as seen in Table 2.3. It also sheds light on some advantages on top of a lower cost and environmental impact, these are relating to mechanical, strength, thermal and energy absorption properties. Further mechanical characteristics of natural biocomposite materials have been studied.

Bourmaud [16] looks at the properties of injection moulded samples through the process of nanoindentation and discusses the effects of moisture absorption within the fibers influencing the mechanical performance. Other studies have shown a more standard approach using tensile testing and scanning electron microscopy (SEM) for analysis [49]. This study revealed an increase in the elastic modulus with more fiber but at the cost of an overall loss in strength. Upon closer inspection of the fracture surfaces, poor adhesion between the fiber and PLA could be the cause of the low tensile results. This is backed up by results seen in biocomposite filaments created under similar conditions [52]. These qualities seen in fiber reinforcement may not be the best compared to known materials such as carbon fiber, but these results provide a base which can be built off and applied in different areas.

Conventional fibers already used in 3D printing using the Mark One duel extrusion system by Markforged are Fiberglass, Kevlar, and Carbon fiber [44, 63]. This printer uses spools of nylon as the polymer filament and a second spool of the preferred fiber seen in Fig. 2-7. The fiber is coated in a thermoplastic, cut to the required length specified by an individual layer and deposited in a similar fashion to current FDM processes. With research into natural biopolymer composites, testing has also been carried out on reinforced biopolymers using 3D printing with additives such as wood fiber printing [23, 45], plant based fibers [16, 17, 31] and cellulose [52]. By venturing into the viability of printing reinforced complex geometries using natural renewable resources, it could open up a much wider range of manufacturing capabilities [18]. These examples seek the goal of producing reinforced 3D printable material, with sights set on increasing the mechanical properties of the virgin materials themselves. One of the main obstacles running as a theme throughout these

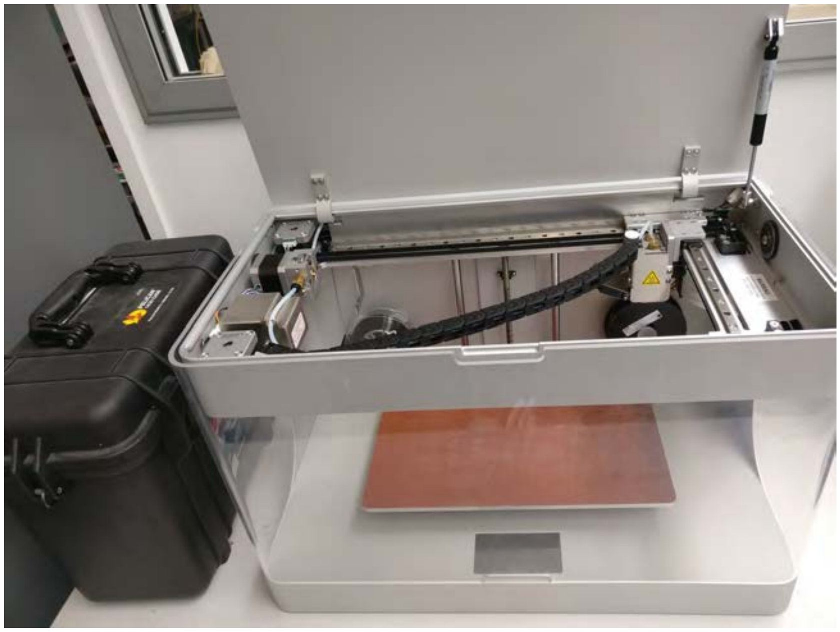


Figure 2-7: The Mark One 3D printer by MarkForged

articles is the moisture sensitivity of the biopolymers potentially compromising the composites integrity.

Table 2.4: Specimen tensile testing properties [54]

Material	Tensile Strength (MPa)	Elongation (%)	Youngs Modulus (MPa)
ABS	19.9 - 29.1	1.5 - 8.9	1910 - 2050
PC	29.5 - 36.9	3 - 6.7	1620 - 2000
PLA	49.1 - 65.5	1.7 - 5.0	2800 - 3600
PLA recycled once	51	1.88	3093 $\pm$ 194
PLA recycled 5 times	48.8	1.68	3491 $\pm$ 98
PLA/PHA + 10-20% fiber	20 - 30	0.9 - 1.1	3500 - 4000
PLA/PHA + 10-20% fiber water saturated	15 - 20	0.5 - 0.7	3100 - 3600
PLA + 5% pine lignin	40.2 - 43.6	2.31 - 2.83	2160 - 2200
TPS/ABS biomass	34.8 - 46.8	NA	NA
PLA + graphite 2%	50	8.1	NA
PLA + graphite 8%	62	6.1	NA
HDPE virgin	25.5	16.1	468..4
HDPE recycled once	25.6	16.1	428.4

2.2.3 Recycling of Material

With 3D printing polymers making steady improvements and pushing development into new areas, access to printers and materials becomes easier and more widespread. Subtractive manufacturing produces larger quantities of waste materials than additive manufacturing, but additive manufacturing still generates waste whether it is degraded SLS powder through re-use or FDM support material. With increases in material production and an insufficient or uncommon means of disposal or recycling, sustainability has become a large factor. A Wohlers Report 2014 prediction mentions the AM market worth is around \$3 billion and estimates an increase to \$21 billion in the year 2020 [41]. With this display of growth, the proposed action is to add a wider variety of material recycling codes and incorporate different ways of applying code visuals onto a 3D printed object, similar to the recycling symbols seen on packaging today. Recycling only makes up a piece of the overall issue of sustainability. The plastics industry is largely dominated by the production of oil base polymers. This in itself is largely contributing to the environmental impact as what is not being recycled will produce a lasting effect [26].

Research has been done around the area of biopolymers for 3D printing with options already available for purchase, as mentioned in the previous materials section. These options do not take away from the mechanical properties seen in commonly used materials and are produced using natural renewable resources. With the creation and growth of opensource household consumer 3D printers, this has prompted the creation of in-home devices to reuse and recycle material. Devices such as RecycleBot, Lyman Filament Extruder and the Filabot accept raw or shredded, used or unused material for processing to create new filament feedstock for printing [11, 26].

The second-hand material can experience degraded mechanical and physical properties when it is recycled and reused. Studies focusing on repeatedly recycling and testing PLA for its versatility and biocompatibility show the mechanical effects as seen in Table 2.4 [26, 67]. The results obtained showed that the mechanical strength, molecular weight and viscosity did decrease; the maximum tensile strength after ten cycles produced a reduction of 8.3%. The viability of recycling like this is very promising, but printing parameters will need to be adjusted accordingly as the viscosity is said to reduce upwards of 80% after the fifth cycle [54].

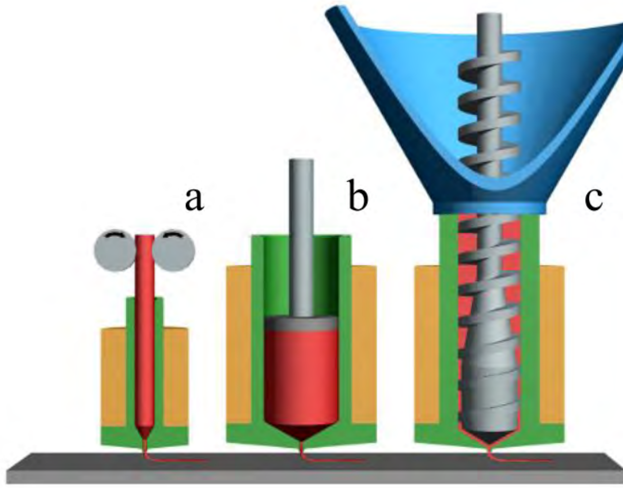


Figure 2-8: Different extruder types; (a) Filament extrusion, (b) Syringe extrusion, (c) Screw extrusion [62]

2.3 Current State of Extruder Technology

One of the most popular forms of additive manufacturing and wide spread forms of 3D printing is to use methods of material extrusion deposition. Though this is a singular category of printer and it is widely known for its filament extrusion open source printers, the method for which material is deposited can vary by design and purpose of the system [62]. These methods vary by the way material is feed into the extruder, how the material is melted, and lastly how the material is extruded and deposited (Fig. 2-8). This section aims to outline the different extruder types and further narrow the selection towards the desired design.

2.3.1 Deposit Extruder Types

Filament Based Extrusion

The most common type of extruder found on extrusion deposition printers and widely used across the consumer market is the filament based extrude. It is very simple in its operation, very controllable and prints using a filament spool of thermoplastic materials. The extruder works by pinching the filament against a roller gripping the surface through friction; the gear that is pinching the filament is attached to a stepper motor to drive it forward and control the feed rate. Extrusion happens by forcing the filament down into the heated tip of the extruder as seen in Fig. 2-8(a). The heated tip melts the end of the filament whilst the solid portion following behind acts as a piston applying pressure and keeping the extrusion rate steady [53]. These extruders are also appealing because of their small size, material range, accuracy and usability.

The rapid prototyping scene has taken hold, with the idea of being able to design, customise, fabricate and manufacture complex objects inside your own home. This started off with the RepRap open source project by Adrian Bowyer in 2005 and has since grown exponentially with many successor variants with tailored consumer needs [15]. Using this type of extruder also comes with disadvantages; many of the problems reside in the material as 3D printing relies on accuracy and repetition. If the filament is too thick it can block the extruder, if it is too thin, melted material can creep backwards up the extruder and cause feeding issues seen in Fig. 2-9(a)-(b). If the pressure applied to the filament is too large the filament can buckle, or the pinching mechanism can slip causing fluctuations in the output Fig. 2-9(c). Other problems that can affect the output are material and residue build in the extrusion nozzle. This causes an increase in elastic-energy due to moisture content in the material, the result can cause die swelling and imperfections such as bubbles or surface roughness [53].

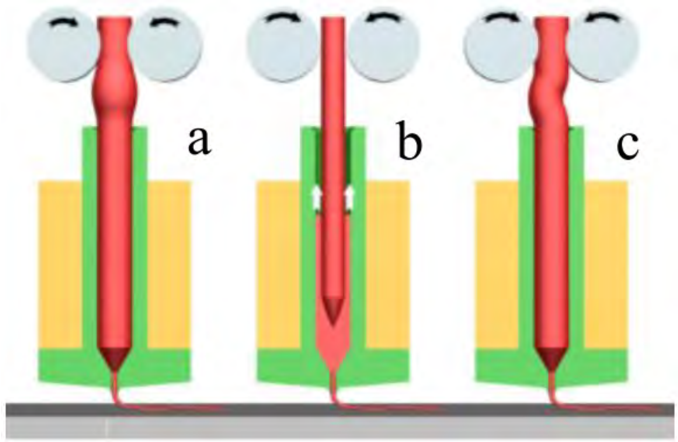


Figure 2-9: Filament extrusion problems; (a) Filament is too thick, (b) Filament is too thin, (c) Filament buckling caused through the pressure being applied on the filament [62]

Syringe Based Extrusion

A syringe-based extruder is a unique system that accepts liquid, viscous paste and low melting point materials. The material is placed inside of a syringe and is controlled by the linear actuation of a plunger in the same manner that filament is driven through the extruder. Because this printing concept does not require the material to be heated, it opens up many more possibilities where viscous liquids are unavoidable or required. One of the more common uses for syringe-based systems is to print foods, these range from chocolate to batter where the printing bed doubles as a cooking surface [9].

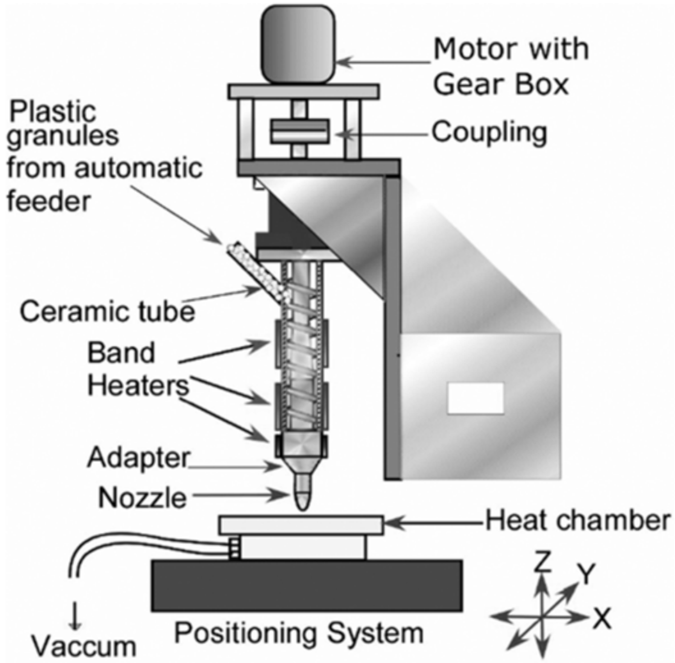
A completely different area is the use of biomaterials and composites. These extend the range of possibilities much further than the common thermoplastics seen within the current printing marketplace, and they are often materials that cannot be formed into filament for extrusion [21]. The technique of 3D-plotting biomaterial inside of a hydrogel medium has been successfully carried out. This uses the control of a syringe to deposit a strand or droplets of hydrogel inks, polymers or ceramic materials inside of a suitable medium [20, 38]. The use of a syringe in this setting allows for the materials to be placed with three-dimensional accuracy inside of supporting materials, in contrast to the common methods of layering. This is where other forms of printing fall short making this a unique process. Additionally, the use of thermoplastic polymer is also plausible but comes with its own disadvantages. If heating is applied to the chamber of the syringe over the course of a print, the polymer can degrade and produce different consistencies during a print. Another problem with this style of printer is the syringe chamber is sealed at the beginning of the process; if the object is too large or the operation carries on too long, the syringe will need to be refilled and may disrupt the printing procedure [62].

Pellet Based Extrusion

Pellet extrusion is very well known and used extensively throughout different industries, but this technology is very uncommon to see used for extrusion deposition modelling [32, 58]. The way a common single screw extruder works can be explained by being broken down into similar terms used to describe current FDM systems as seen in Fig. 2-10. The material is typically in solid pellet form (alternate molten state) and placed into a hopper as the delivery method to the extruder. The pellets are massed into the flight of the extrusion screw which transports the polymer through a plastication process. In a common system the pellets are largely melted by shear forces generated through friction, assisted by heaters mounted around the barrel. When melted, the screw pumps the polymer to the end of the extruder where the molten material is forced through the die head taking the shape of the opening [57].

Some of the advantages relating to screw extrusion are low material and running costs, material can be added directly to the extruder even during processing, leaving no down time and removing extra processing which can lead to degradation. The selection of polymers is increased beyond the boundaries of filament production with the advantage of being able to introduce additives and mix combinations without extra processing [62]. A disadvantage in designing a small scale system like this is the knowledge around extrusion design lies in large scale industrial processing, the implementation and scaling of this knowledge does not translate well into a small scale rapid prototyping device [24, 60]. Other disadvantages include a higher risk of stray particles contaminating the extrudate, and many more operating parameters around temperatures, pressures and speeds to maintain the correct output. Because these devices are more complex it leaves more room for error.

Figure 2-10: Pellet extruder and positioning system [58]



2.3.2 Screw Extrusion

The process of extrusion was roughly talked about in reference to 3D printing, this section aims to break down the more fundamental processes involved to narrow the options for a simplistic and beneficial small-scale 3D printer design. Extruders can be categorised into two types; the first is continuous (Fig. 2-11). Continuous extruders operate around a rotating member to extrude a continuous length of material. This is commonly a screw, but some designs use a disk instead.

The second type is discontinuous. These are often referred to as batch extruders and use rams to press out material like syringe extruders. They are suited for short-burst operations such as injection moulding as seen in Table 2.5. In terms of a 3D printing, a reciprocating extruder, although plausible, would not be suitable for printing some higher temperature material compositions. These could obtain degrading effects over long motionless periods of heat exposure.

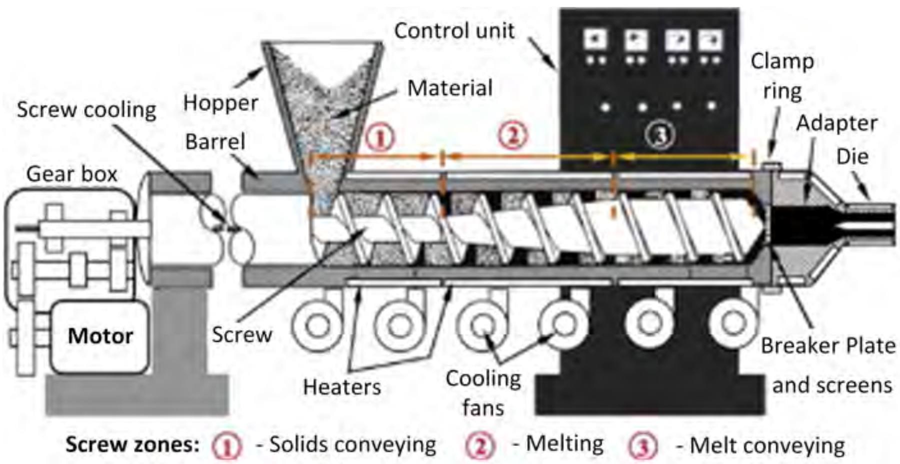


Figure 2-11: Common single stage continuous screw extrusion system [27]

Table 2.5: Classification of polymer extruders [57]

Screw extruders (continuous)	Single screw extruders	Melt fed
		Plasticating
		Single stage
		Multi stage
		Compounding
	Multi screw extruders	Twin screw extruders
		Gear pumps
		Planetary gear extruders
		Multi (>2) screw extruders
Disk or drum extruders (continuous)	Viscous drag extruders	Spiral disk extruder
		Drum extruder
		Diskpack extruder
		Stepped disk extruder
	Elastic melt extruders	Screwless extruder
		Screw or disk type melt extruder
Reciprocating extruders (discontinuous)	Ram extruders	Melt fed extruder
		Plasticating extruder
		Capillary rheometer
	Reciprocating single screw extruders	Plasticating unit in injection molding machines
		Compounding extruders such as the Kneader

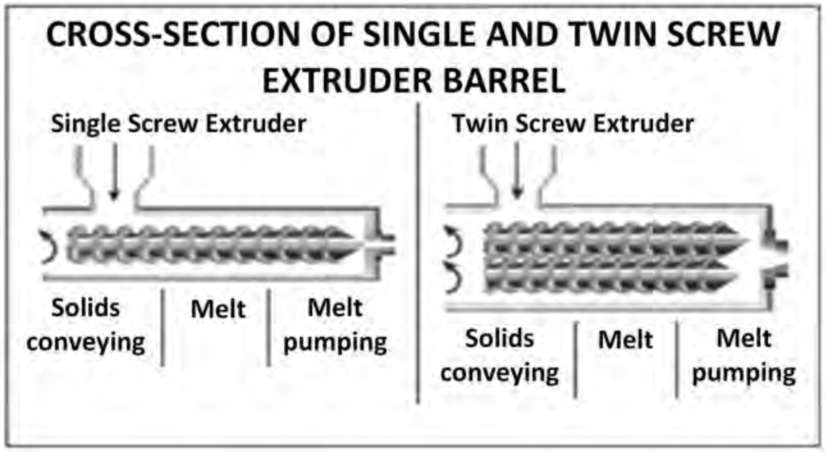


Figure 2-12: Single and twin screw extruders [55]

Continuous Screw Extruders

For continuous screw extrusion, the screws can be broken down into two types: common single screw design, and multi-screw design (Fig. 2-12). The most fundamental and the commonly used design is the single stage single screw extruder. The single stage refers to the single compression zone in the screw, but the screw itself can often be divided up into three distinctive sections. These sections are the feed section where the material enters the system, alterations to the screws channel depth or the addition of an agitator, cramming or starve mechanism inside the hopper can provide benefits to the inflow of material [47]. Secondly comes the compression or transition section where the channel depth is reduced resulting in a compression of the overall volume. This feature is to generate friction to help with material transportation and to generate heat. The heat created contributes to reaching the materials melting point often with the aid of external barrel heaters.

Once the material has exceeded the melt temperature and has fully transitioned to a molten state the only task remaining is to transport the polymer to the die head to be forced out. The final section of the screw which transports the melt is called the metering or pump section. The final piece of the extruder is the die. This piece of the system opposes the flow of material and therefore requires a greater amount of force to extrude. As the material passes through the die it takes the shape of the opening(s), therefore the smaller the opening or the more complex the channel design, the larger the resistance and the greater the force required to extrude [57].

The procedure for multi screw extruders is typically much the same as a single screw extruder, but it can also be very different leading with the example of a twin-screw extruder. By adding another screw, the number of geometrical combinations greatly increases, therefore the way that materials are processed can occur in many more ways. The core difference between a single and a twin-screw extruder is the conveying of the material; single screws are less complex and are used in profile extrusion processing. Twin screw extruders are more complex with a more tailored approach towards sensitive and specialised material processing and are capable of high speed extrusion.

A twin-screw configuration prevents massing of material through inter-meshing of the screws. This factor also results in the melt forming before it reaches the compression zone, therefore generating a lower pressure than single screw designs [47]. Twin screw extruders are often expensive and if there is difficulty in predicting the processes performance, or the process needs to be changeable, a modular system is required, further driving the cost up [57]. For the application of small scale 3D printing, a twin or multi-screw extruder does not have any outstanding or must have features and may not be worthwhile implementing.

Extruder Monitoring Control

The extruder design is only a piece of the system; if there is no means of monitoring what is going on throughout the process there is no way of maintaining or improving the quality of the output. The reason this is important is because it provides information when a problem occurs and allows for troubleshooting. Monitoring of an extrusion system includes the process temperature, cooling, motor speeds, pressure generated and power usages. Although these are not all of the possible measurements, the most important factors of an extrusion process are the temperature of the melted material; this could be in several locations along the barrel. The second being the generated melt pressure [57]. The pressure generated behind the die affects the flow rate of the output; variations in pressure cause the output to also be affected. The same goes for the melt temperature and screw speed, if the temperature fluctuates, the materials viscosity can change affecting the output flow.

There are many approaches to control the system with methods based around monitoring and controlling temperatures, speeds and pressure, and others based around the resultant melt viscosity. A range of methods are used such as Proportional Integral Derivative (PID), adaptive controls, fuzzy logic, mathematical models and even statistical techniques to determine trends [10]. The devices used to monitor the pressure are often pressure transducers commonly located near or in the end of the extruder, but there is no restriction to how many a system has; often multiple measurements are taken at designated zones across the length of an extruder to gather the whole process in one picture. The sensors themselves come in a variety of forms with different accuracies, pressure ranges and sensitivities. Temperature sensors are similar, in that they have a variety of choices across different ranges, therefore it comes down to the application as to which ones are selected.

Extruder Screw Design

This section will discuss screw design in terms of single screw extruders with information around common types of screw, screw properties and their function. A screw extruder revolves around the screw; it guides the process from when the material enters the system to the material being extruded from the system. In between the entry and exit, the screw may contain many different designs and considers all sorts of complex factors in order to convey and process the material effectively. The functional design purpose of an extruder is to be as efficient and productive as possible, producing the highest quantity of possible output with an acceptable quality. When designing a screw, it is best to consider the limitations of the process to create the desired efficiency [57].

There are many factors that go into the design of a screw, some of these include the rigidity of the screw to withstand the forces generated, spacing/width/angle/clearance of the screw flights and the channel depth. These few design considerations all have effects on the performance and material transport characteristics and should be taken into account when designing a large-scale process line. A screws design can come in many different forms, but to simplify things further, they can come with a single helix along the screw or with multiple flights. The more standard single screw design only has a single flight, this design is widely used but not the most optimal design, modifications such as additional flights, pitch and zone changes are made to aid in optimising material transport and compressions. By adding additional flights, you can improve performances through increasing the frequency of material feeding in, a higher melt rate and better transfer of material [57].

The design of a screw is like putting together a puzzle, the difference being specific geometries are put into the desired zones to isolate the effects and program the material process. This is seen in the design of barrier screws developed and patented in 1959 by Charles Maillefer [48]. The barrier placed along the screw as a secondary flight has extra clearance between the barrel to only allow for molten polymer to pass over, thus separating out the solid material. As the barrier continues along the screw, the solids channel becomes compressed and the melt channel volume grows. The solids channel eventually compresses and merges back into the melt channel. This method ensures all of the solids are melted [57]. Although a barrier can aid the melting process, it can also cause a build-up of material preventing the flow and cause impurities in the output [47].

Modifications to a screws design have been made in efforts to improve processing. Similar attempts and changes have also been made to designs for improvements in mixing capabilities. Mixing can be categorised as, either dispersive or distributive mixing. Dispersive mixing is primarily utilised to break up any masses or agglomerates of material, while distributive mixing is

Table 2.6: Comparison of Dispersive Mixers for Single Screw Extrusion [57]

Mixer	Pressure drop	Dead spots	Barrel wiped	Cost of mixer	Number of passes	Distributive mixing	Type of flow
Blister	High	Some	No	Low	1	Poor	Shear
Egan	Fair	No	Yes	Fair	1	Fair	Shear
LeRoy/Maddock	Fair	Yes	Yes	Fair		Fair	Shear
Fluted CRD	Low	No	Yes	Fair	>1	Fair	Elongation
Zorro	Low	No	Yes	Fair	1	Fair	Shear
Double wave	Low	No	Yes	Med.	>1	Fair	Shear
Energy transfer	Low	No	Yes	Med.	>1	Fair	Shear
Helical LeRoy	Low	No	Yes	Fair	1	Fair	Shear
Planetary gear	Low	No	Yes	High	>1	Excellent	Shear
CRD mixer	Low	No	Yes	Fair	>1	Good	Elongation
CB mixer	Low	No	Yes	Fair	>1	Good	Elongation

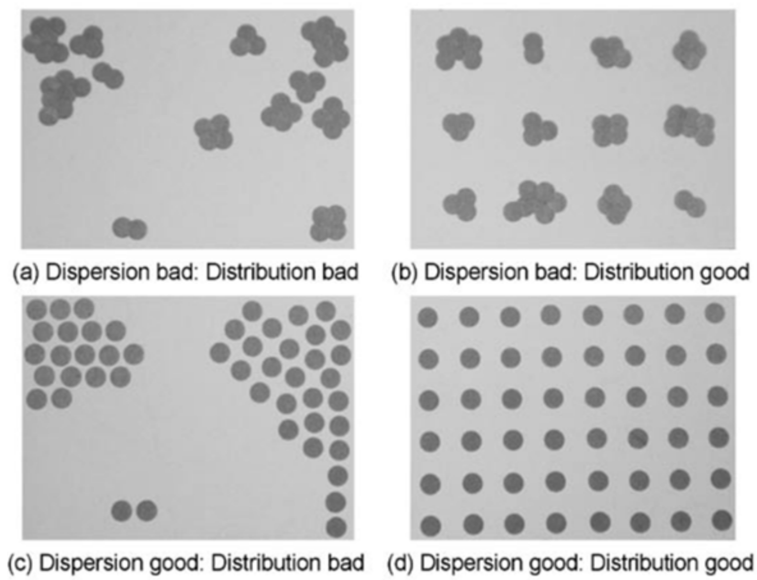


Figure 2-13: Screw mixing type comparison [33]

used in the blending of separate materials in the attempt to distribute them evenly [33]. Fig. 2-13 provides a visual representation of the different mixing types. A few of the more common or effective dispersive mixers are shown in Table 2.6 and it also shows the distributive capability.

2.3.3 FDM Platform Designs

With any extrusion deposition printer, regardless of the way that extrusion is achieved, the object being created must be within a defined space. In terms of extrusion printers, the most common platform design uses a Cartesian x-y-z coordinate system to work within. Although this coordinate system is simple and common there are many ways in which platforms have been designed to travers and print within this coordinate space. Common printing platforms seen on the current market come in many forms each with their own advantages and disadvantages. The widely used cartesian platform offers a very robust, affordable and accurate design used by many researchers as an adaptable platform but is also still used today by the original patent holder Stratasys, Ltd [25].

There are also many spinoff models and designs made by the opensource community such as the CoreXY with the extruder as the x-y plane. Some of the openly available designs improve build volume, others focus more on accuracy and many seek to improve affordability. With such a large community behind this design it makes it easy to source materials and information to better understand and adapt a platform to suit an individual's needs.

Other types aside from the typical Cartesian printer are delta platforms which use three separate arms that are connected to the extruder at a common point. The arms are controlled independently in the vertical direction to manoeuvre the extruder inside the build area. This platform offers a large build volume in the vertical direction and structure allows for very quick movements. It has a cylindrical coordinate space but can be restricted in the x-y plane due to the spread of the arms.

The Polar platform is similar but has many features that are unique. This design, unlike the delta platform is a more compact system and uses the round base to manoeuvre in the x-y plane. Another very different design utilises a SCARA robot configuration with either one or two horizontally suspended arms holding the extruder. The arm controls the x-y plane with either the arm assembly or the bed moving in the z direction. One downside of these arms is when they are extended outwards it puts a lot of stress on the joints meaning the extruder needs to be very light or deflection could occur [3, 4].

Other systems have been developed that expand on the Cartesian coordinate system. The BLACKBELT 3D printer changes the angle of the extruder to print between 15 and 45 degrees onto a treadmill like circulating platform. This platform design allows the print to extend off into infinity allowing for a continuous part with the limitation of width and height [5]. A further advancement in printing on a sloped surface is the development of a filament extruder on a robotic arm with 6 degrees of freedom. The platform can print like a regular deposition printer, what sets this printer apart is its printing envelope which breaks the boundaries of traditional cartesian systems. It can angle its end effector to print on an incline by manipulating its reference plane and printing otherwise angled objects in a vertical fashion removing stepping [43].

2.4 Summary of Findings

The goal of the presented literature was to explore a broad spectrum of additive manufacturing to find a means of effectively printing with biopolymer materials and experiment with composite additives. Many biopolymers are unable to be printed in resin or powdered form. Additionally, these materials make experimentation with composites more difficult. It was found that a majority of AM experimentation is carried out using extrusion deposition systems. These results also revealed efforts towards recycling printed materials, this could be carried out on external filament extruders using shredded material.

By exploring the different methods of extrusion deposition printing, the method that would suit the proposed objective and benefit long term was narrowed down. Although filament-based printing is the most commonly used, screw extrusion offers more room for development and could be far more adaptable when experimenting with additives, even offering the ability to recycle material without separate processing.

Finally, the research focusses on the technology within screw extrusion to define a method suitable for a miniature extrusion system. With any extrusion method, in order to print, the system needs a platform to print with. Therefore, a search into more common platforms was carried out to find a robust and adaptable option to support the needs of this objective.

Chapter 3

System Design

There are three fundamental parts of a melt extrusion 3D printer; the extruder, the mechanical scanning platform and the control systems (Fig. 3-1). An extrusion-based 3D printing system depends on the extruders ability to reliably and accurately output the correct quantity of material over varying distances. The accuracy of the extruded material is obsolete if the mechanical axis is inaccurate or has limited capability, therefore, accuracy for both the extruder and axes are needed to create aesthetic and geometrically correct parts. Filament based extrusion is already well established in the 3D printing marketplace, with a large open source community behind it. With such a large backing comes the availability of support and modifications to improve and freely design compatible systems.

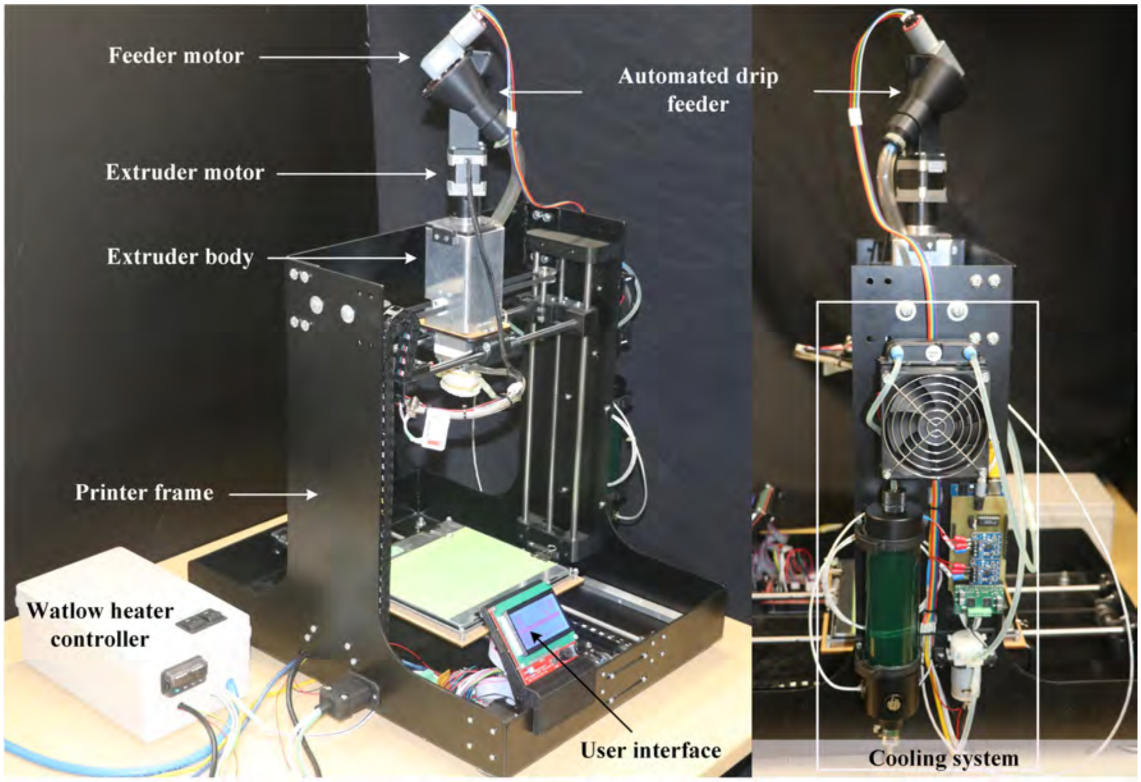


Figure 3-1: Pellet printing platform and extrusion system

3.1 Platform Design

To create an accurate and reliable platform, the design needs to support a miniature screw extruder with a hopper. This must take into consideration the larger footprint and weight of the extruder in comparison to common FDM systems. On top of this, the platform needs to work with the current open source configurations for ease of use and customisation. The design also needs to allow for adjustments by allowing enough space around the extruder, in case the build volume increases with modifications or if additional components are added. From the research on available printer platforms, these were seen to be the most common styles of platform available (Table 3.1).

From these options the Cartesian platform was chosen for its support base, reliability and customisation options. The delta configuration, although popular, would not be the most suitable option for this type of extruder. The arms would need to support a larger weight, the pellets being fed in could get shaken up causing transport inconsistencies and the calibration acts more as an inconvenience. The polar and SCARA printers are both compact designs, but these options do not offer anything more to benefit this process than the Cartesian designs.

The platforms design was based around a 200mm cubed build volume with considerations

Table 3.1: Styles of different printer platforms, outlining design positives and negatives

Printer Type	Positives	Negatives
Cartesian	• Robust and simple • Easy calibration • Easy to find/solve problems • Many varieties • Variety of software available	• Some designs can be weak in structural design (e.g. Crane) • Can have a small build volume
Delta	• Quick print speed • Great accuracy/reliability • Large build volume	• Locational print resolutions • Suspended extruder with rapid movements • Calibration and error detection can be difficult
Polar	• Very compact design for the build space • Uses a circular grid system	• Does not seem to be as popular so it will not be as supported
SCARA	• Compact device	• Needs extra support and tight tolerances to reduce/avoid deflection and joint movement

made around the size of the extruder. The style of Cartesian printer chosen has the extruder bed operating as the y-axis, the extruder is attached to the x-axis and the x-axis is vertically controlled as the z-axis. This configuration is basic and does subject the extruder to movement, but its simplicity provides a few benefits: reduced cost from the minimal complexity, easy error detection due to independent axes, and a stable structure with minimal spatial restrictions.

To operate and control this platform three pieces of opensource software are used. The first is the slicing software 'Slic3r' that is used to break up a model into layers, generate the printing path for each layer and export the path instructions as g-code. This software is widely used and easily configurable; it offers control of most aspects of the printing process making it the perfect choice for custom configurations.

Secondly, the software interface that monitors the system during the printing process is 'Pronterface'. This software reads the sliced g-code file and sends the instructions to the printer over a serial port whilst also monitoring the feedback from the printer to make sure the printer is within parameters.

The final piece of software is the g-code interpreter which is configured on the on-board electronics of the printer. The chosen board is a Ramps v1.4 running on an Arduino Mega 2560 and the software running on it is 'Marlin'. This software has configurable settings to define the working of the printer itself, the step rate of each axis, mechanical settings, temperature controls, limits and platform configurations. By defining the workings of the printer, the software can interpret the incoming g-code commands and accurately act out the printing system instructions.

Table 3.2: Types of extruder used in extrusion 3D printing, outlining positives and negatives

Filament Extrusion (Positives)	Simple mechanism allowing consistent and accurate flow
	Extruder prints in many orientations
	Can hold a large spool of material
Filament Extrusion (Negatives)	Higher materials cost and limited range
	Materials go through an extra process to form filament
	Additives also need to go through the filament making process
Syringe Extrusion (Positives)	Can extrude heated or cold liquid materials
	Extrudes complex composite materials
	Useful for extrusion and placement of cellular materials
	Can be extruded in any orientation
Syringe Extrusion (Negatives)	Material degradation with prolonged chamber heating
	Restricted quantity of material before refill
Screw Extrusion (Positives)	Low material costs and wider range of materials
	Material mixing capabilities
	Additive and composite blends are possible
	Can recycle material without extra processing
Screw Extrusion (Negatives)	Particle contamination
	Complex system monitoring
	Heavier extruder, platform type restrictions
	Restrictive print orientation
	May need to refill material during print
	Output problems; bubbling, surface, clogging, consistency

3.2 Extruder System Design

It is not necessary that the extruder is only filament based; an FDM printer only requires a controllable flow of material to deposit in layers. The method of extrusion presented works by using a screw as the feeding mechanism to transport pellet materials into a heated zone and then forces it out of a die. Some advantages of different extruder types are shown in Table 2-8. A screw extruder is more complicated when compared to the other methods such as filament or syringe extrusion. By using pellets, it opens up more room for error and greater chances for inconsistencies, but offers more material flexibility. Where heating similar materials using a syringe could have degrading effects on the polymer over the course of a print. Therefore, for this work we adopt a screw based extruder design.

It is very rare to see the use of a screw extruder in an FDM printing system. The goal of a screw extruder is still to produce a reliable and consistent output of material, the difference is that there are additional parameters to monitor and the system is more prone to fluctuations. Large scale extrusion machines rely on many parameters to provide stability and accuracy. The two main parameters used to determine the working conditions are temperature and pressure. When shrinking such a large-scale machine to be part of a 3D printer, some compromises had to be made to the extruder for the intended operation. Therefore, this system requires considerable thought and testing to determine what system design works best.

The extruder design is largely based on a full sized single screw extruder. The design includes a hopper system to feed the correct material quantities, an extrusion screw to transport the polymer, an extrusion die to shape the melt output, a drive motor, and lastly the heating and cooling system. For all of these parts to seamlessly work together, a considerable amount of testing and analysis is required. Because this is not an exact process, the printing platform must also be able to accommodate any unforeseen changes to the extruder design.

Figure 3-2: Image showing the relative size and shape of the PLA pellets used in testing and composite blends

3.2.1 Material and Extrusion Type

The project objective is to develop a small-scale 3D printing platform to process and print different combinations of biopolymer materials. The research presented in Section 2 concluded that more potential lies in the development of a screw extrusion platform for this type of process study. The method of extrusion selected falls under the widely used single screw category for its simple, robust and reliable design. Currently there are very few consumer printer models on the market that offers a screw extrusion system for easy adaption to suit our needs [7, 2]. Lack of available research on similar methods make it difficult to replicate their results and the designs are often too bulky.

The main polymer being used in extruder calibration and as the primary element in the testing of composite blends is virgin Polylactic Acid (PLA). The pellets provided for this are cylindrical in shape and of varying sizes between 1 and 3mm (both diameter and height) Fig. 3-2. The composite fibers being tested are Harakeke flax fibers, these were provided as a PLA blend and come as different percentages from 15wt% to 30wt%. The more fiber present in the blend, the more unpredictable the testing can become. The PLA on its own can absorb a large quantity of moisture from the air, but mixed with the fibers the moisture content tends to be retained a little more during the drying procedure. The moisture content can lead to air bubbles forming in the output causing breaks in the extrusion road and also increases die swelling. The fiber mix tends to discolour and can burn if the polymer is to convey slowly through the extruder, or is left stationary. The final testing polymer was virgin Polyethylene Terephthalate (PETG), it was used to explore and challenge the extruder's capabilities. In comparison to PLA, PETG has a higher melt temperature, a much finer line between very viscous and fluid-like, and it also soaks up a generous amount of moisture.

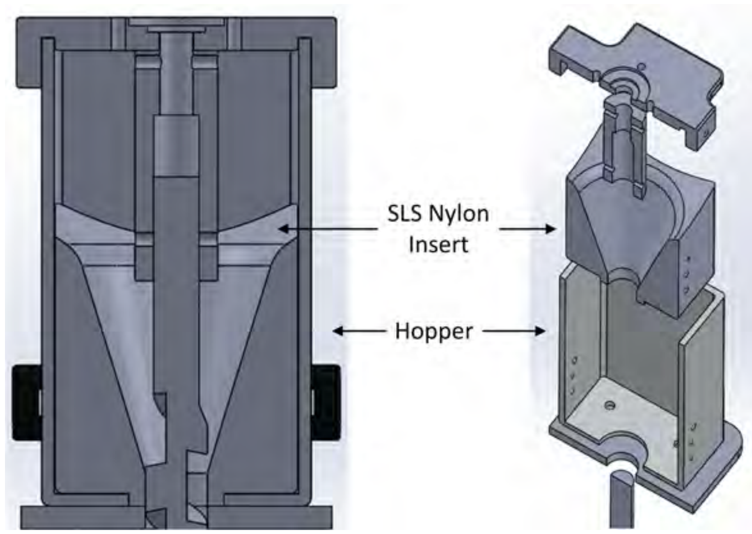


Figure 3-3: (Left) Assembled cross section view, (Rigth) Exploded cross section view

3.2.2 Hopper Design

The most popular every day 3D printers or consumer printers use filament as the way of extruding materials. The filament feeding technique normally uses a gear to pinch the filament for grip. Coupled with a stepper motor these printers can accurately control the feed rate. Because of the uniformity in material input and a precise feed rate the output becomes very consistent.

Although pellet extrusion has been around for a long time, the implementation of it in 3D printing is currently very uncommon. Printing with pellets becomes more complex when trying to obtain consistency. Where material is introduced to the extruder it has a longer list of things that can go wrong, and the process is not as easily controlled. Instead of a filament reel to hold the material, a hopper is used in this design to hold the granular sized pellets for the screw to carry into the system, other types of system can accept powders and pre-melted material [24]. Often the way pellets are fed into the extrusion process is with the assistance of gravity, and in some cases the hopper is assisted by an agitator or stirrer. This works well with common systems having the screw mounted perpendicular to carry the polymer horizontally from the hopper, but this extruder design has the screw vertically in-line with the hopper. Even in this case the hoppers job remains the same by acting as a guide for the pellets to flow. In this design the pellets are added into the hopper as they are picked up by a protruding screw channel rotating inside the hopper Fig 3-3.

Later in the design process, a drip or starve feeder was added to aid in the extruder's consistency by feeding small quantities of pellets periodically (Fig. 3-4). By adding a large quantity all at once, the result is an inconsistent transportation of polymer ending in the extruder jamming or variations in output. This partially due to the extruder being vertically mounted and the screw

Figure 3-4: Images showing the dripfeeder with motor attached and the seperate guidance tube

passing up through the middle. If the hopper has too many pellets inside, the large grouping acts like insulation preventing the rising heat from escaping. If this happens, the pellets soak up the heat past their glass transition point and end up sticking to each other. This leads to grouping which prevents the transport of material and eventually starves the extruder. To achieve a consistent flow of material through the primary hopper, the rate and quantity of material entering the system needs to be controlled.

3.2.3 Proposed Extruder Design

The extruder is the fundamental part of any extrusion deposition system and requires considerable thought, testing and analysis to produce a practical design. The design of a pellet-based extruder for a 3D printer is very similar, in many ways, to a conventional pellet extrusion process. It is a simple full sized single screw extruder miniaturised to work within a consumer sized 3D printing platform. The designed capability of this extruder is to produce a continuous and consistent output of material for 3D printing and testing purposes. The proposed system is designed to operate using a single vertically mounted screw, where the polymer feed is controlled and delivered using gravity. A drip or starve feeder controlling the polymer input, a hopper to guide and hold the material, a heating band to heat the polymer and a liquid cooling loop around the neck of the extruder.

The most common screw type used with a single screw extruder, is a single compression stage continuous extrusion screw which can be divided up into three distinct sections as seen in Fig. 3-5(a). The polymer is driven from its solid pellet form through a plastication process where material shearing is utilised to generate heat and movement, thus changing the materials viscosity before being extruded. The output forces required by the drive motor to generate the necessary friction would not be suitable for the scale of this 3D printer. Not only will the system be large, heavy and potentially slow, but repeated stop/start actions when printing will put a lot of stress on the drive motor.

This prompted the screw design to take a more unconventional turn. Instead of using a driven method of extrusion which would require overcoming a great deal of frictional force, a more subtle approach was taken by relying on gravity to initiate flow with minimal applied force to generate movement. A modified auger drill bit was chosen with the single purpose of delivering the polymer to the heating zone and pushing the melted polymer through the extrusion die. By not having a metering or compression zone on the screw it reduces the required torque and stress acting on the drive motor, and further opens up the drive choices for a lighter, more controllable system.

To obtain the accuracy and consistency needed to print, the input of material is slowly introduced to the printer at roughly the same quantity as the output over time. This method is to prevent blockages from occurring at the entrance to the screw. As the heated air rising through the system it can become trapped and the material becomes sticky preventing it from moving down and reaching the melt zone. To aid in preventing blocking, a liquid cooling band is placed around the throat of the extruder. This is to prevent excessive heat from rising into the hopper and causing the material to stick around the feed opening.

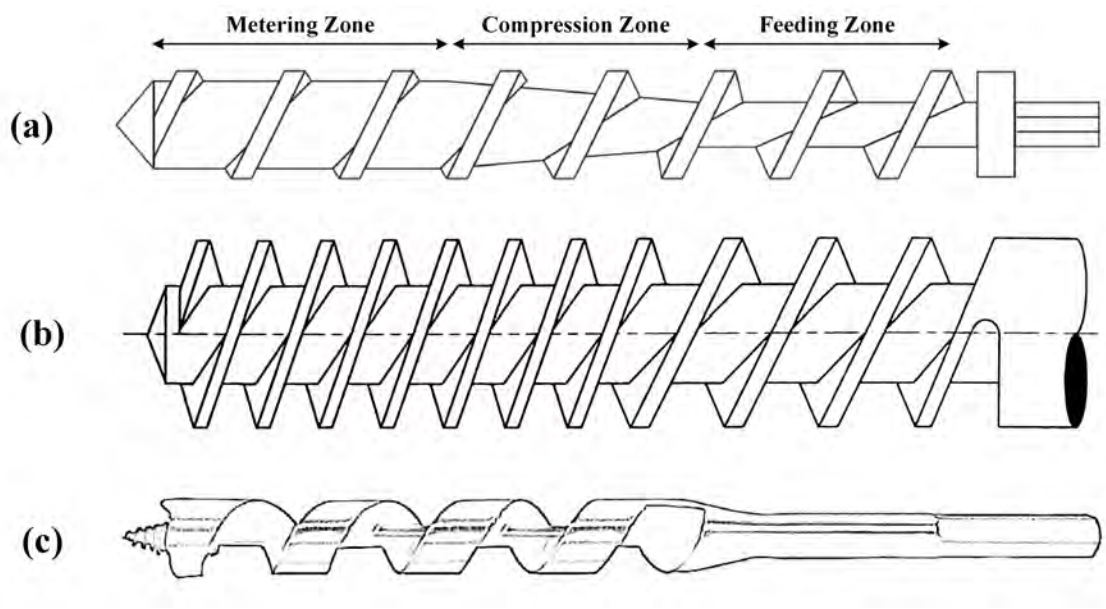


Figure 3-5: (a) Common single compression or three stage continuous extrusion screw [47], (b) rubber extrusion screw [57], (c) wood auger drill bit

Complete Extruder Design

Because this system is made with small scale 3D printing in mind, this design came out in an unconventional way for a screw-based extruder. Large frictional forces, long heavy barrels, and big motors do not fit the 3D printing picture very well, so an adapted design has been developed to output the desired profile with printing characteristics. The feeding mechanism in common filament-based systems transports the material from a spool by using a gear pinching mechanism to grip the filament. A motor then drives the material through the heated extrusion tip. This mechanism allows accurate control over the feed and extrusion rates as well as providing the ability to stop and start between paths and layers. A single screw pellet extruder has a similar purpose, but screw extruders are generally designed for continuous operation at a specific extrusion rate and require more control over the temperatures and pressures generated along the screw. For this extruder to perform as a 3D printer, there are a few changes that need to be made.

A common industrial sized single screw extruder takes the polymer feed through a multi stage plastication process, it then forces out the resulting melt through the die head. Typically, the objective of a continuous extrusion screw is to output the largest quantity of melted polymer at an accepted level of quality. Because a small 3D printer is not necessarily operating with a continuous process, the extruder and screw will need to be tailored to suit the operation. Therefore, not every aspect of a large-scale extruder is practical to include in this miniature design as the purpose for each is quite different. An extruder screw is typically made up of three zones, the feed, the

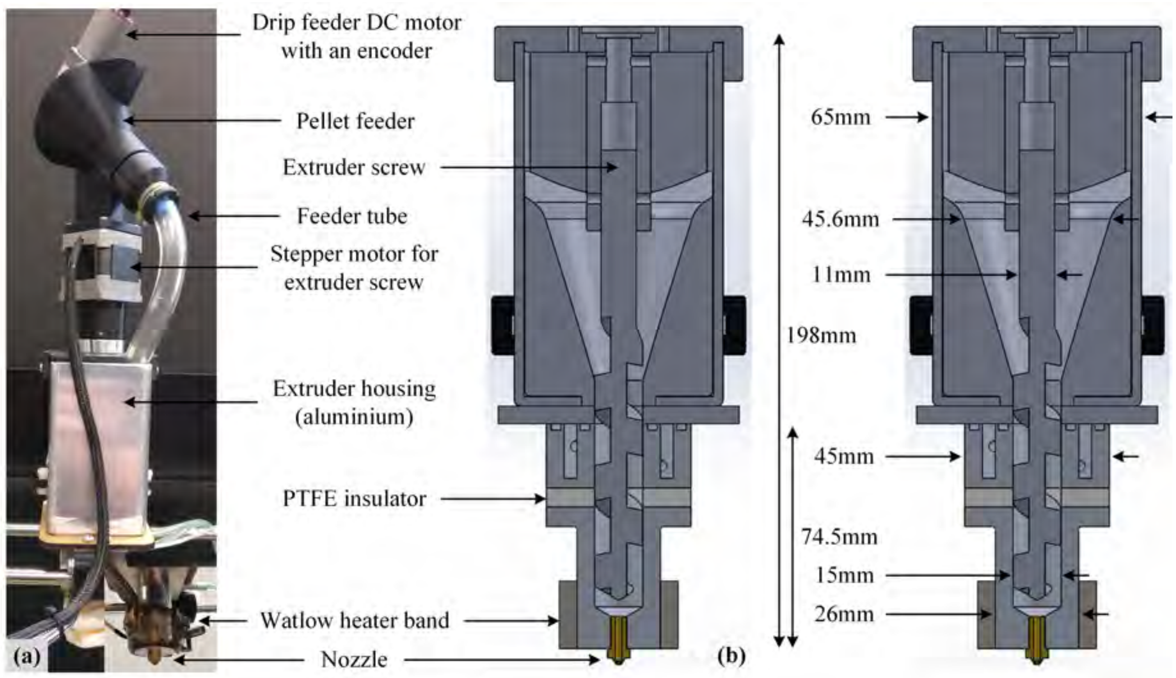


Figure 3-6: (a) Entire extruder system mounted in the printer, (b) full SolidWorks assembly of the extruder

compression and the metering zone as seen in Fig. 3-5(a). The screw is designed for the type of polymer and process to generate the correct pressure, temperatures and speed for the desired continuous output. In a normal case, the screw is not only the forward movement of the polymer, it also largely contributes to the heat generated to melt the polymer through shear in the material.

In this design, the focus is not on generating heat through material friction because that adds unnecessary stress on the drive motor which would mean a larger motor and a bulkier system to support it. Instead, a large majority of the heat to melt the polymer will be generated from a heating band, so the screw's job in this extruder is to transport the material to the melt zone and then pump it out of the die head. Therefore, inspiration for the screws design fits with a rubber extrusion screw which can have a reduced length, an equal channel depth along its length, and are built for both hot and cold material feeding Fig. 3-5(b). A compromise was made in the miniature design with an inexpensive 15mm diameter auger drill bit which resembles similar features to a rubber extrusion screw as seen in Fig. 3-5(c).

The requirements of the single screw extruder do not see eye-to-eye with its industrial sized counterpart. The printing processes of an FDM extruder requires the flexibility to adjust extrusion rates, stop and start between paths and layers, produce a consistent bead of material, and be light enough to traverse the platforms axes. The extrusion screw used in the proposed design does this by reducing its task to simply feeding the material straight into the melt zone without a compression section as seen in Fig. 3-6. By not having other screw zones, the required length of the screw only needs to be short. Pellets undergo little shearing, thus reducing the axial and radial forces acting on the screw which reduces the strain on the motor. This, in turn, provides better control over the output because the motor does not have to fight against strong friction forces allowing the screw to stop and start with greater printer functionality.

Because this is easier, the extruder can be made lightweight with a NEMA 17 stepper motor combined with a 19:1 reduction gearbox to provide a 5 Nm stall torque to power the screw. To reduce the weight further, the material used to make an extruder barrel was made from aluminium. This choice helps with machining time for prototyping purposes and provides quite a reactive thermal conductivity for reducing the start-up time and improved cooling. The downside to using this material is its hardness, because it is quite soft wearing occurs at a faster rate where the clearance between the screw and the barrel is quite tight.

Figure 3-7: (Left) The Watlow 200W resistive heating band mounted at the extruders tip, (Right) Watlow PID single phase controller

Heating and Cooling System

There are a few different types of heaters applied to extruders. The job of a heater in large scale systems is to initially raise the extruders temperature to soften the material and start the screw rotating. Once the screw has started, a majority of the heating is generated through the plastication process. There are three different types of extruder heaters: fluid, steam and electric [57]. Electric is the most commonly used form of heating as it provides more control and less restriction over a range of temperatures. Their cost is often lower than other systems and they are easily maintained. With better control over the heating, large systems can create a thermal gradient along the length of a screw by placing multiple monitored heaters.

Although heating is monitored during extrusion, the heaters themselves are frequently used to maintain correct zone temperatures for an efficient process (about 20% of the energy input). In larger scale extrusion systems, the screw is used to produce a majority of the heat through material shearing or friction, essentially using the materials viscosity against itself. The two options for electric heating are resistance heating and inductive heating. Because inductive heaters require resistive metals to generate heat efficiently and the extruder design is made using aluminium, the chosen method of heating is using a resistive heater (Fig. 3-7). This method is more common and relies on current flowing through a path with high resistance to generate heat.

The design for this extruder is quite short and does not rely on temperature profiles or shearing to form the melt. Instead this simplified system acts in a similar way to a filament extruder where the heating rests on the very end of the extruder. The heating band used in this extruder design is a

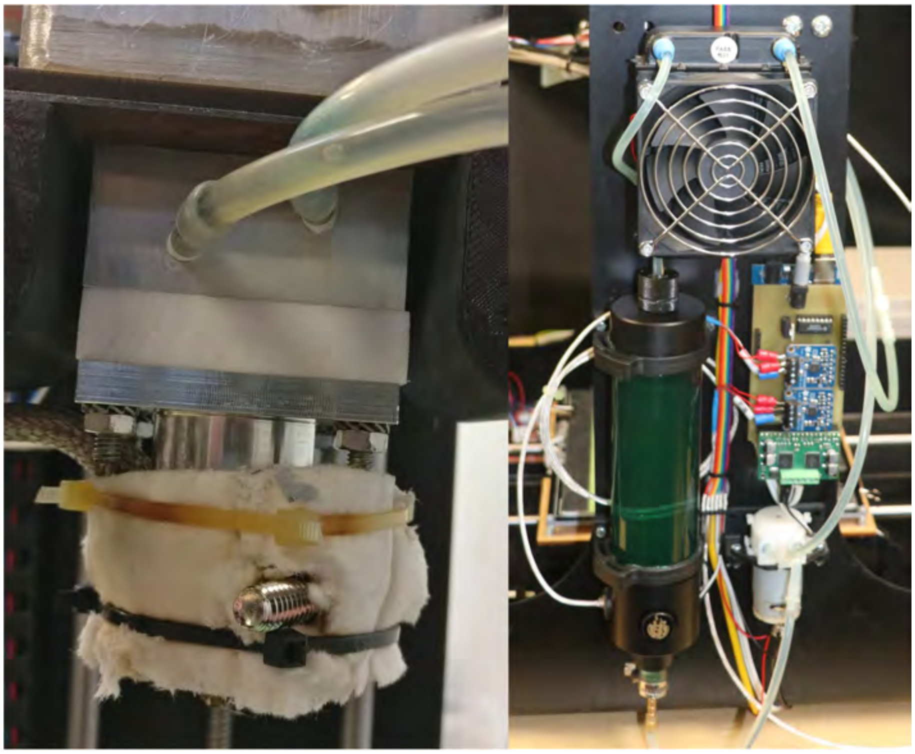


Figure 3-8: (Left) Coolant block around the neck of the extruder and the Teflon barrier, (Right) radiator, coolant reservior, pump and control temperature/feed controller to complet the loop

200W 240V AC resistive Watlow band heater. This type of heater was chosen because it allows for an easily adjustable range of temperatures with minimal maintenance and built in temperature feedback. Within the current extruder's implementation, the heating control is monitored and adjusted by a thermistor inside the band heater by a Watlow EZ-ZONE PID controller in Fig. 3-7. 3D printing often requires rapid stop/start control of the extruder for small features. It is for this reason that generating heat through the use of a continuous compression driven screw would not be practical in this operation.

Where there is heating, there is also cooling. This is a contradiction to the overall process as it is directly taking away energy put into the system, which lowers the efficiency of the system. In large production extrusion lines, cooling and energy loss can contribute to high costs over an extended period of time. This is because taking away energy from the system is effectively wasted energy, but in most cases, it is essential for maintaining optimal process temperatures. The ideal scenario is when cooling is not required in the first place, but in reality, the compromise is to try and minimise it as much as possible. The most commonly used cooling types are air-cooling and fluid cooling. Air is used when a gradual, smooth cooling effect is required; fins are placed around critical cooling areas for increasing the effective surface area. Fluid cooling is a more aggressive form of cooling which rapidly removes heat from a contact surface; the coolants used are often water or oil.

In a small-scale system, cooling is very necessary for the intended process functionality because the heat covers a small area and does it very quickly. The most frequent problem that occurs when there is insufficient cooling, is a blockage. This happens when the temperature rises up through the extruder and causes the material to reach its glass transition temperature before entering the extruder. This is not the easiest problem to solve, especially with such a small system and material such as PLA with a low transition temperature of 50°C. The heat problem comes from multiple sources: the heat propagates up the screw, through the walls and rises as hot air. Testing and analysis revealed that air-cooling was able to work for periods of up to about 15 minutes but was insufficient in removing enough heat over an extended period of time.

The current active design focuses on preventing this by adding a water-cooled channel around the neck of the extruder to remove the heat propagating through the walls and some of the heated air. This alone is not enough as the water will eventually boil away. To solve this, a block of Teflon or PTFE (Polytetrafluoroethylene) was inserted below the water block as a thermal barrier (Fig. 3-8). This acts in multiple ways: firstly, it has a low thermal conductivity which drastically lowers the amount of heat that reaches the water block. By doing so, the boiling water is prevented and the cooler's long-term effectiveness is increased. Secondly, Teflon has a low coefficient of friction which prevents material from sticking to the wall, therefore, during transport, the material no longer sticks to the water-cooler wall and Teflon barrier, thus heavily increases the chances of reaching the melt zone. The water runs through a 12V peristaltic pump at about 40ml/min around the water block channel. From there it runs into a small radiator using a 90mm fan for cooling. The cooled water then runs into a 380ml PC coolant reservoir and then back to the pump to complete the circuit (Fig. 3-8). The reservoir is large enough and the flow rate slow enough that a decent amount of heat would also be lost though the cylinder's walls before being re-circulated.

Chapter 4

Development of Printer Systems

4.1 Extruder Platform Development

Along with the design and fabrication of an extruder, the creation of a platform that would accompany and support this extruder also needs to be designed. As previously discussed in Section 3.1, the frame needs to be secure and stable enough to hold an extruder that is heavier than ones more commonly used in filament extrusion yet produce an appropriate level of accuracy. The design process started off with the selection of the platform category seen in Table 3.1. This was later narrowed down to the simplistic Cartesian style designs for robustness and open source support.

To begin designing a Cartesian printer that can handle the extra weight and size of the extruder, the available Cartesian designs and their factors need to be considered. The chosen design (Fig. 4-1) uses a belt driven, x and y setup with two parallel leadscrews for the final z-axis. From the side, the printer looks like an upside-down capital 'T'. The print bed is the y-axis only with the extruder movable on the x-axis and the x-axis vertically movable along the z-axis. This design offers a robust, simple and inexpensive solution that can be reinforced to accommodate the proposed extruder.

This style of printer is popular among the open source design community; an example with similar features is the Prusa i3 printer. Other styles, such as having a crane design, offer little structural support by solely relying on the vertical guide support of a single side. Another common design uses a triangular frame seen throughout the RepRap Mendel range. It offers simplicity and a sturdy structure, but the top of the printer is closed off which would end up restricting the height of the extruder. The final common design suited this type of printer and platform design is shaped like a cube. The design has a dedicated z-axis motor at each corner with the x and y-axes on the

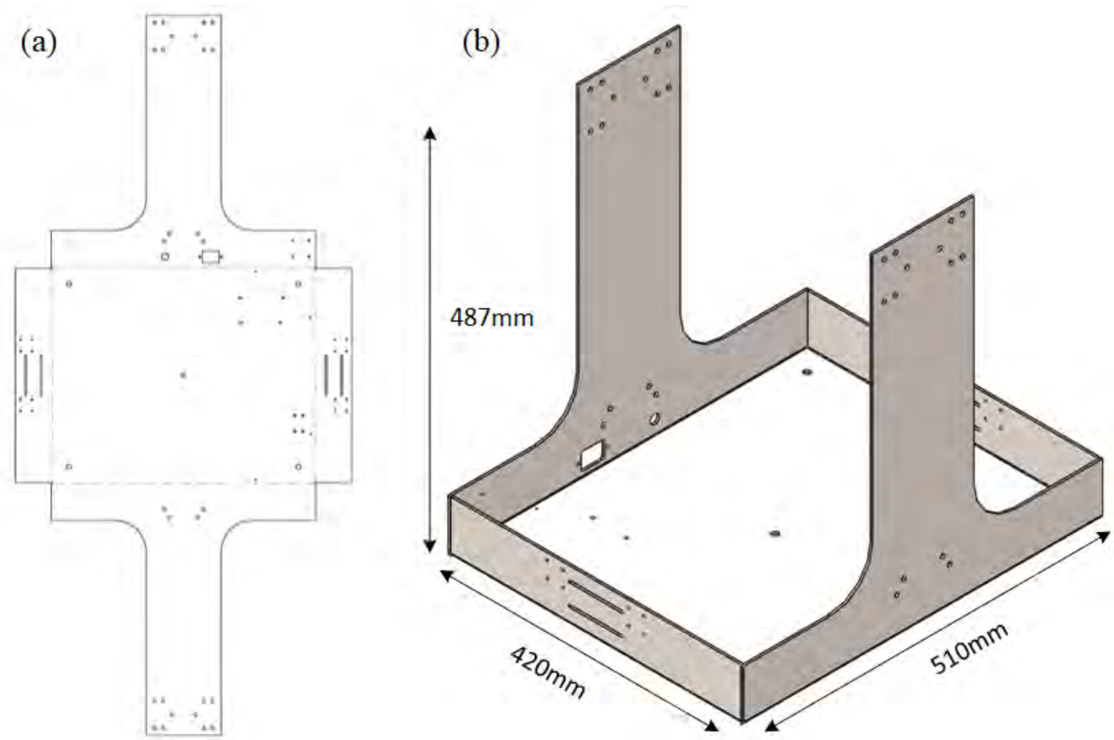


Figure 4-1: (a) Flat sheet metal view of the frame design, (b) Folded sheet metal view with scale dimensions

same plane. The x-y axes could be either the movement of the bed or the extruder, and the z-axis could be either the movement of the extruder upwards, or the bed downward. It would be optimal if the pellet extruder remained stationary, but in either case the system is more complex and results in a larger than necessary cost.

The frame of the printer is designed and made using 3mm steel sheet metal, the major structure is a flatpack design to be cut out using an on-hand steel laser cutter to then be bent into shape, as seen in Fig. 4-1. The entire platform design is based around open source configurations to fit with popular hardware and software configurations as well as to maintain a low cost. To maximise hardware compatibility, the motors that were selected for this were NEMA 17 standard footprint with a 1.8° step angle and 0.4Nm of torque. The guide rails used for every axis were 10mm stainless steel linear rods with linear bearings to accompany them Fig. 4-2(b). The movement of the x- and y-axes is achieved through the use of tensioned GT2 belts and pulleys Fig. 4-2(c), whereas the z-axis uses two 400mm Tr8*4 leadscrews Fig. 4-2(a). Lead screws were chosen for extra support and reliability in lifting the weight of the x-axis plus the extrusion system. Once the axes were assembled, the support weight of the z-axis movement comfortably exceeded three times the operating weight.

The internal connections and braces were the result of rapid prototyping using an ABS filament 3D printer and added extra support to account for stresses during operation, shown in Fig. 4-2 as

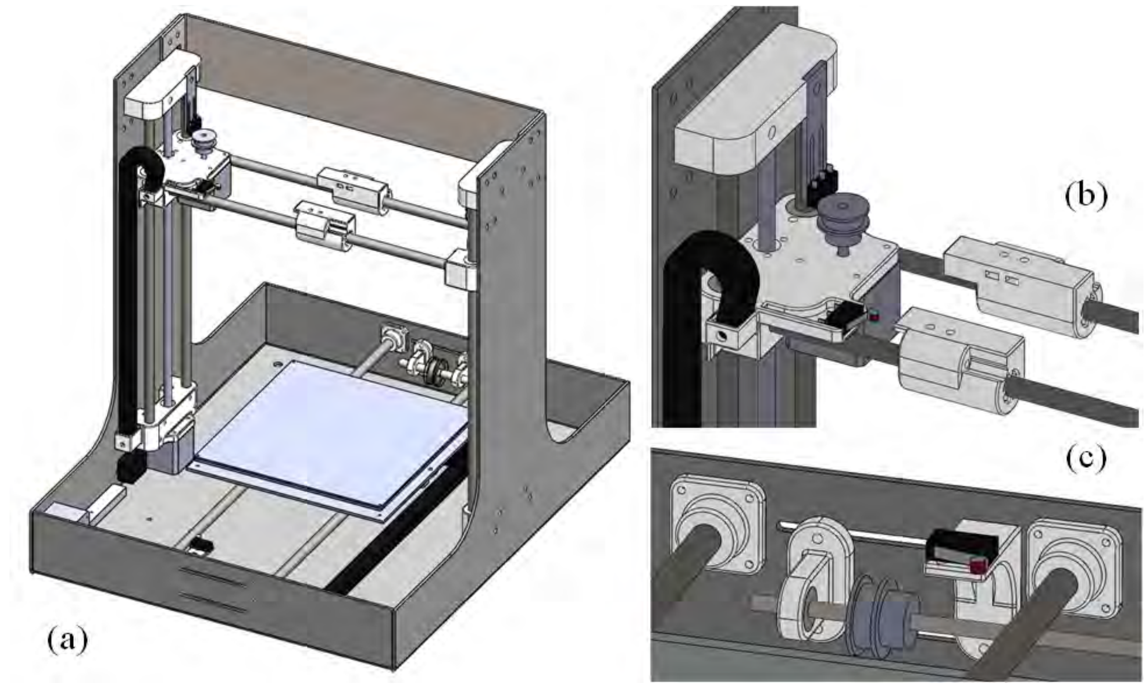


Figure 4-2: (a) Overview of the assembled model, (b) Close-up of the x/z axes custom joints and sliders, (c) Custom mounts for the y axis

white parts. By modelling and printing these parts they will not have the best mechanical strength, but they do allow for easy modification and adjustment for any future changes.

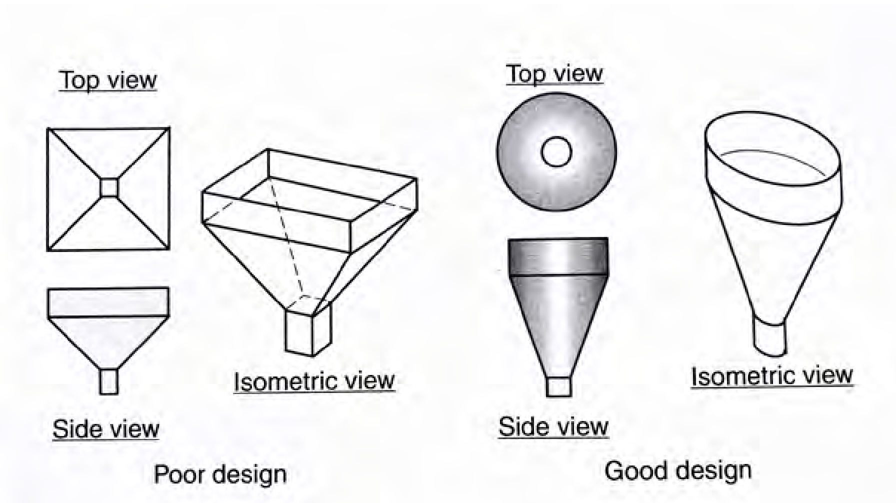


Figure 4-3: Drip feeder good and poor design considerations [57]

4.2 Extruder Design Process

4.2.1 Hopper Development

One of the main attractions of a filament extrusion system is the consistency and reliability of the output. This comes from the uniformity of the material being pushed into the extruder, as well as precise control over the feed rate and temperatures. The trouble with pellets is they have a certain degree of unpredictability, with varied sizes, shapes and material characteristics.

The shape of the hopper and sloped angle can help improve pellet flow characteristics by preventing any material sticking to the wall. To reduce any conveying problems the implemented hopper was designed to be cylindrical in shape as a square hopper has corners that have the potential to cause feeding issues Fig. 4-3. This design has the screw in line with the hopper, so it acts as a guide for the polymer to flow into the throat of the extruder.

The original hopper design was developed by a past student who made several models, these ranged from a square acrylic box to a printed square funnel shape and finally to this SLS 3D printed round funnel hopper made of Nylon powder Fig. 4-4. These model changes came about as a result of poor thermal and flow characteristics causing heat to travel throughout the system resulting in material building up and the hopper itself warping during extrusion. The final model removed most of these problems by improving the thermal properties of the hopper and changing the internal curvature to better accommodate the transport of non-uniform pellets.

Although improvements were made successfully in the previous project, when implemented

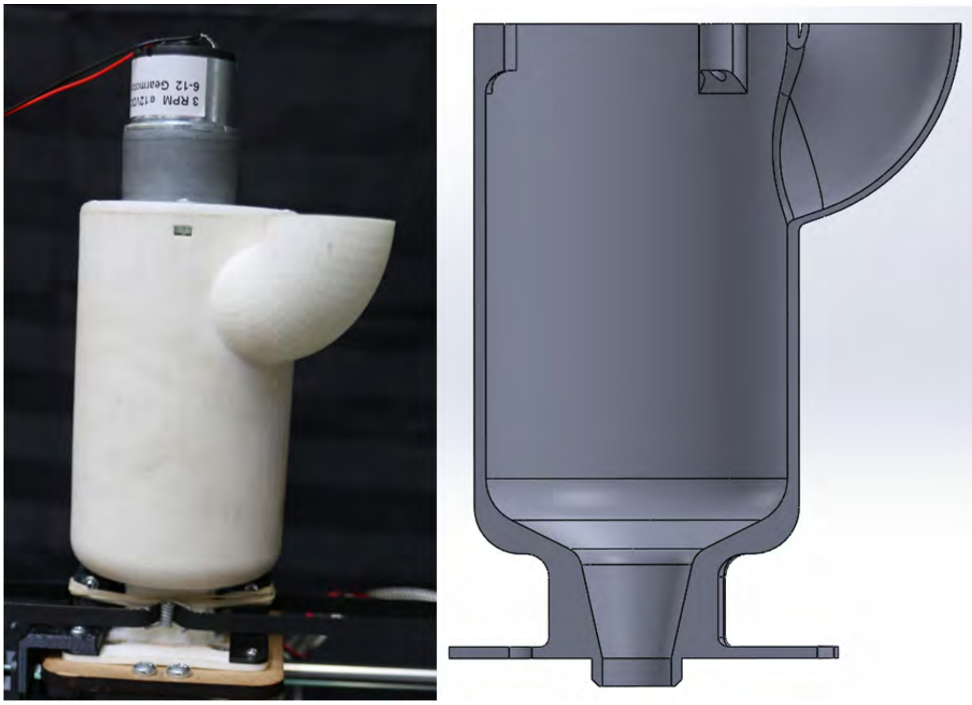


Figure 4-4: (Left) SLS printed original hopper design, (Right) Solidworks model of the original hopper

Figure 4-5: (Left) Flexing and deformation causes pellets to be force out, (Right) internal veiw of escaped pellets

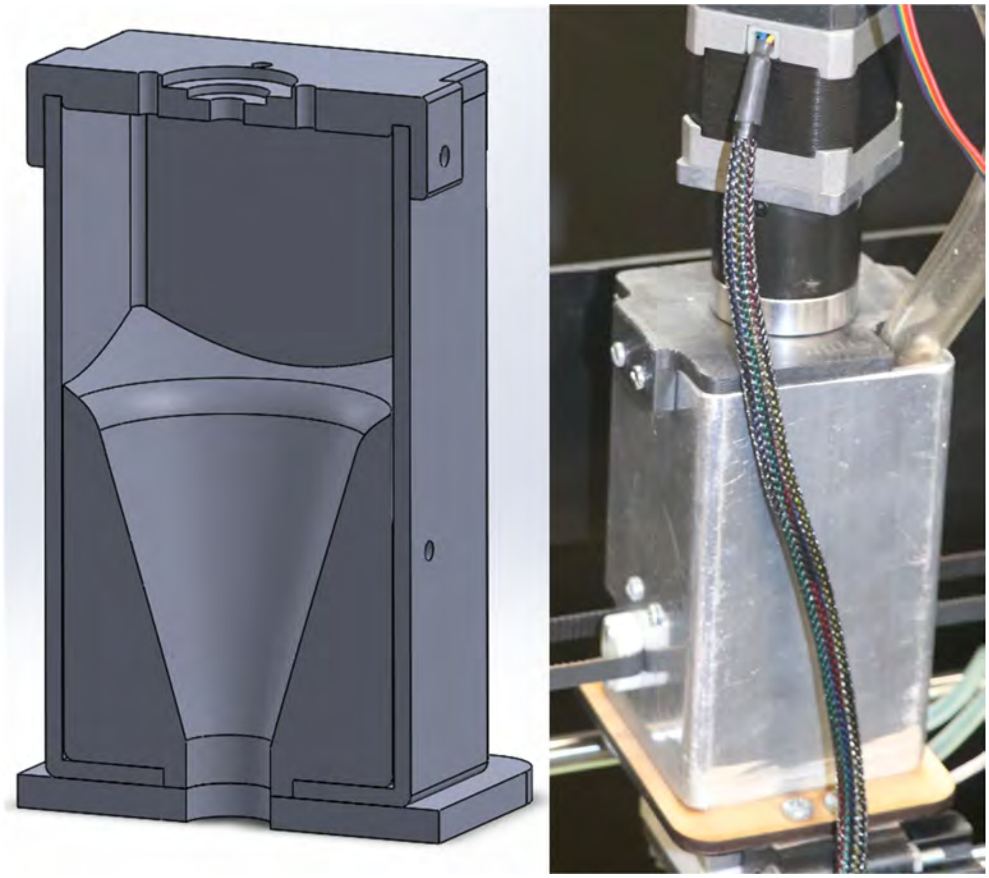


Figure 4-6: (Left) Sectioned view of new design in SolidWorks, (Right) Application of new hopper design

in this setting the hopper revealed further problems. The hopper experiences deformation as the pressure generated inside the extruder exerts axial forces on the drive motor. Because the drive motor is directly connected to the hopper, it is relying on the strength of the hopper to apply enough opposing pressure for extrusion to occur. But because the hopper is not rigid enough, the hopper deforms and the result is pellets forced out around the neck of the extruder seen in Fig. 4-5. This was previously solved by screwing down steel plates around the neck to stop any flexing, but this design could not support those fixtures. With attempts to supress this issue, it led to the discovery of a more severe problem. If the pressure somehow grew too large during printing, the hopper also starts to twist. This is caused by the extrusion motor being mounted to the top of the hopper where it generates a torsional load on the structure to create the forces necessary for extrusion. The output of polymer was severely affected, often the bead of polymer would bulge and shrink with the rapid changes in pressure.

To solve the rigidity problem present in the hopper system, a redesign was required. As seen in Fig. 4-6 the external structure and base of the hopper were designed and made out of 3mm aluminium box extrusion, thus removing any visible twisting and improving the power transfer into the extrusion process. The hopper is situated on a piece of MDF which locates the hopper to the extruder bore. This fixes the extrusion system to the x-axis guide rails and also helps slow the heat transfer through the system. Although it was previously mentioned that a square hopper was of poor design and promoted material build-up, to improve this a conical nylon SLS printed insert was added to the interior of the aluminium hopper and fixed with external screws (Fig. 4-6(Left)). As nylon worked well against heat exposure in the last model, it was reused. The insert was made at a sharp angle to alleviate any possible frictional effects that different materials may have. If the insert had not worked as intended, it was a much easier process to design a new one and replace it rather than make a whole new hopper. For testing purposes, the lid was 3D printed using ABS. The testing resulted in such a huge improvement over the last hopper version that a more permanent fixture was not developed.

Although filament extruders are of a simple design, there is still the occasional issue. These include material building up on the filament pinching mechanism, lowering the contact friction creating slipping. Similar issues also occur if too much heat were to climb up the filament or reach the pinching mechanism, and if too much force is applied to the filament it causes a buckling effect and prevents extrusion. These issues raise the question: if a simple, well-controlled filament system can generate so many feeding problems, how is a more complex pellet feeding system going to generate consistency? Because most pellets come in different shapes, sizes and often have edges after being chopped up, their flow characteristics can vary and quite frequently stack together preventing movement. As the proposed extruder is mounted vertically, the main hopper has a limited effect as pellets added are not actually being fed into the system, it is only acting as a guide. Therefore, buy adding a means of control over the number of pellets fed into the hopper, the whole hopper system can feed the extruder and avoid potential bottlenecking, thereby reducing inconsistencies.

To achieve a consistent flow of material through the primary hopper, the rate and quantity of material entering the system need to be controlled. Restricting the feed of material can also increase mixing capabilities on top of the reduced chances of material building up [57]. A drip feeder has been designed with the job of preventing a build-up of stationary pellets in the hopper absorbing heat Fig. 4-7. This was the first design attempt at controlling pellet materials by creating an extruder like screw feeder. It works simply by opening a slider, pouring in material and letting a screw control the transport of pellets to the outlet. This did not work as intended because the body was SLS printed creating too much flex for materials to push up against and causing a jam. Therefore, a new design was modelled to allow pellets to flow around the centrally mounted screw and work their way towards the outlet via the guidance of a gradual slope (flow channel) Fig. 4-8

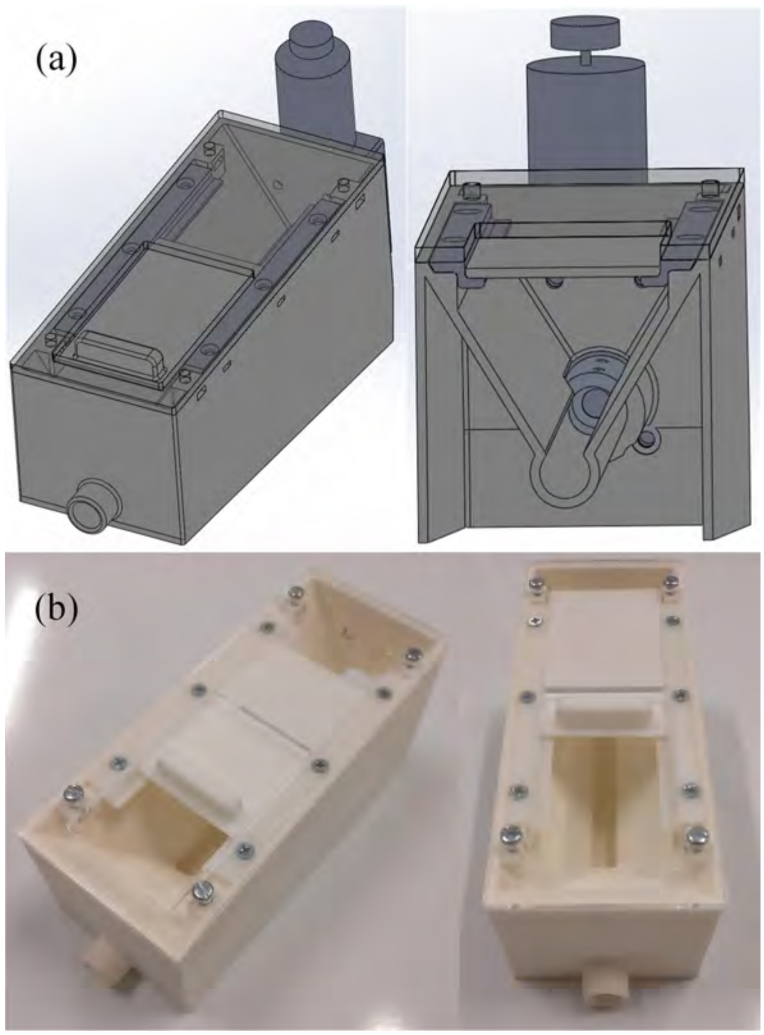


Figure 4-7: (a) SolidWorks assembly of initial feeder design, (b) SLS printed initial feeder design

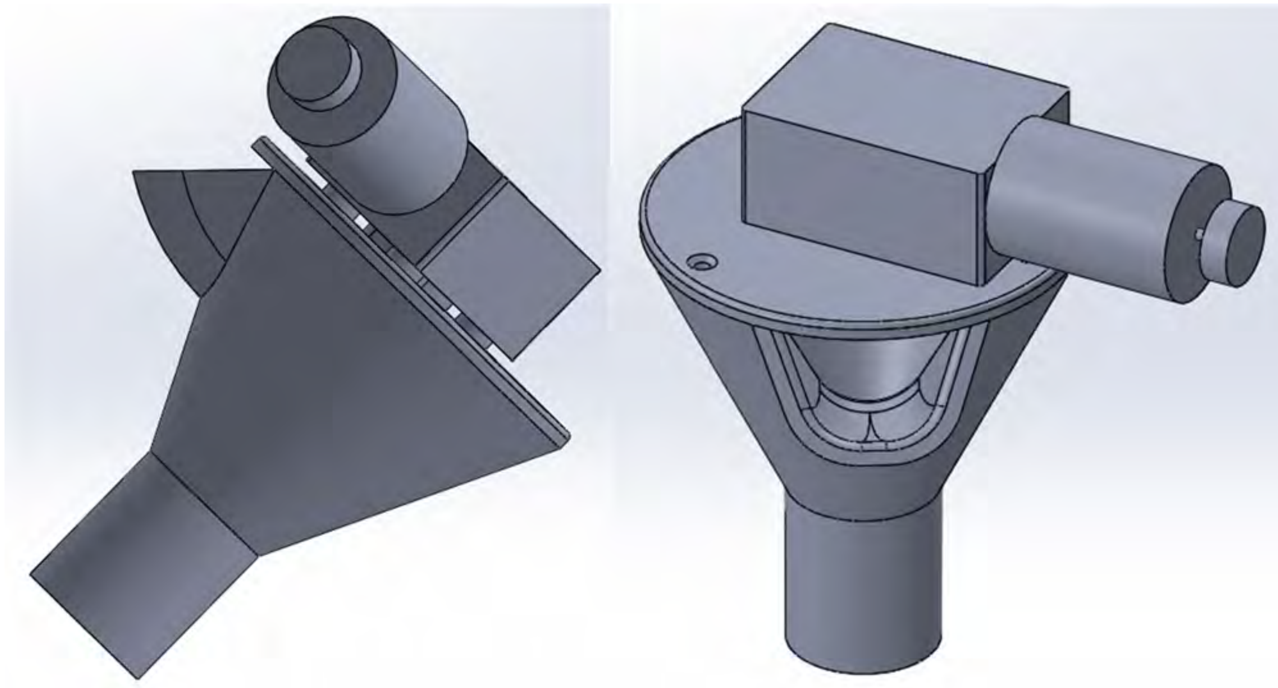


Figure 4-8: SolidWorks model of the new feeder design

The feeder is of similar shape to the main hopper's conical shape, this is to remove any possibility of edges affecting pellet movement. The feeding hopper uses a modified 10mm auger drill bit to transport the pellets at a programmed rate. The feeder is designed in three pieces to be mounted on top of the existing hopper and to guide small pellet quantities down a tube into the main hopper (Fig. 4-9). The main piece of the feeder is the conical chamber where a large quantity of pellets is poured inside before printing begins. The second part is the mount that sits on top of the extruders drive motor, this holds the feeder in a consistent manner over the hopper. Lastly there is a 12mm inner diameter rubber tube with a printed fixture that friction fits onto the end of the feeder. This bridges the gap between the extruder hopper and the feeder, providing both stability to the feeder and unrestricted flow. There is a 12v 40rpm DC driven worm gear with an encoder attached to the feeder's auger, driving the material out at a set quantity per minute whist feeding back information. More on how the motor is controlled in Section 4.3.

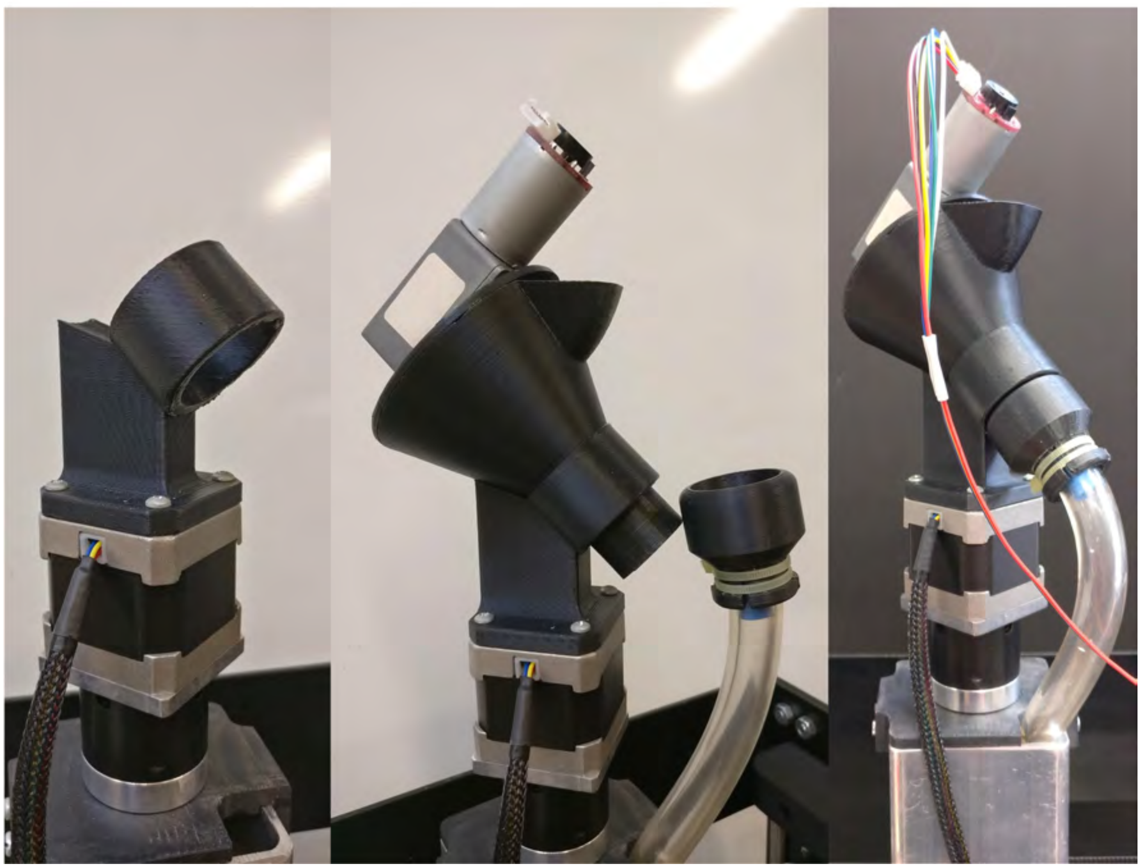


Figure 4-9: (Left) Feeder mount on top of extruder motor, (Middle) feeder friction fits inside mount, (Right) full feeder assembly with guidance tube into main hopper

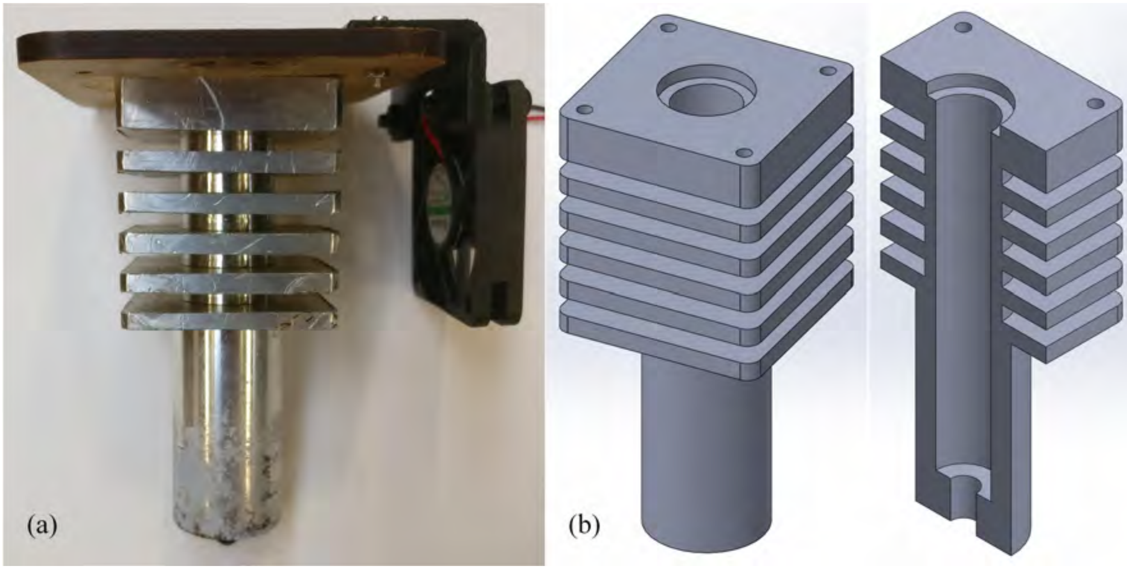


Figure 4-10: (a) Air cooled extruder with 40mm fan mounted, (b) SolidWorks model of the air-cooled extruder

4.2.2 Cooling System Development

At the beginning of this project, the extruders method of cooling began with air cooling around the top of the barrel. The heating design used the same 200W Watlow heat band as previously described to heat up the end of the extruder and form a melt zone. The fan used in this model was 40mm in diameter and runs on 5V DC. Cooling fins were machined around the upper section of the extruder's barrel to increase the barrels surface area where the material enters the screw, overall increasing the effectiveness of cooling (Fig. 4-10). This location was to prevent the heat traveling into the hopper and partially melting pellets that had not entered the barrel. The results of this design were inconsistent and often caused material to clump together and eventually block the transport of material. It did succeed at slowing the build-up of heat initially, but after several minutes the heat would creep inside the hopper and disrupt the process. At one-point the cooling fan melted due to the immense heat generated around the fins.

It was determined that the cooling from an air-cooled design was not effective enough. One solution could have been to improve upon the air delivery system by adding an additional fan, directing a more focused airflow. Alternatively, there is potential in using a misting system to humidify the air for better heat transfer. The chosen direction was to move to a more common practice of liquid-cooling using water, as this method is known to have a more aggressive heat transfer and because it is inside a closed loop, it provides more consistency than air cooling.

This design uses the same idea of reducing the heat around the throat of the extruder, but in-

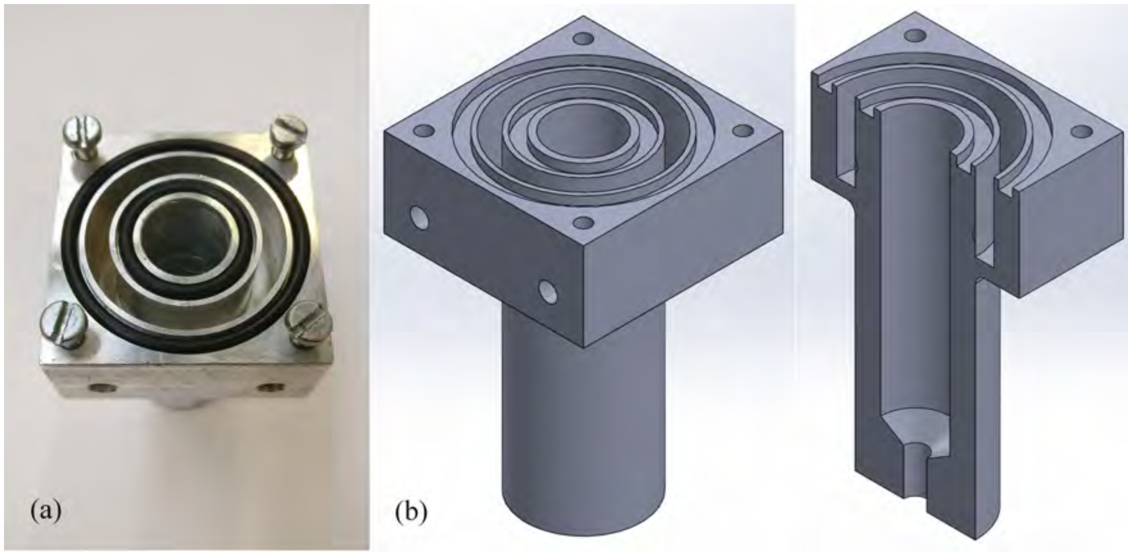


Figure 4-11: (a) First water cooled channel design, (b) SolidWorks model of initial water-cooled extruder

stead this is done by adding a water channel around the barrel (approximately volume is 6.4ml) as seen in Fig. 4-11(b). The design of the channel is very simple, there is one large groove milled into an extended block around the barrel. To let the fluid in and out of the channel there are two threaded holes cut into the side of the block. To prevent any leaking, a pair of O-ring slots are milled on either side of the channel to be compressed by a plate, thus creating a water tight seal Fig. 4-11(a). The water is pumped around the coolant loop using a 12V peristaltic pump through soft rubber tubing with a 3mm inner diameter and the pump delivering approximately 40ml/min as shown in Section 3.2.3 Fig. 3-8. The 12V pump can be directly wired into the printers control board for instruction and manipulation through g-code.

Prior to the first test run, a transparent piece of acrylic was secured to the top of the coolant block and the circulation was checked to make sure the water that was pumped into the channel flowed. The loop was then primed to make sure there was no trapped air, PLA was prepared inside the extruder and the system was turned on. The first observation using a multimeter's temperature probe (thermocouple) was that the extruder's heat transferred rapidly through the aluminium, where the difference between the heating band and the neck of the extruder were only a few degrees apart.

As the melting temperature of PLA is close to 160°C, when the heating band temperature was rising to meet the melting temperature, at around 140°C the water in the cooling block would reach boiling point and turn to steam. In an attempt to prevent this, the pump was turned on before the water reached boiling point. This would cause the heating process to stall as the extruder's temperature would stop climbing and never reach the melting temperature. If the pump was cycled

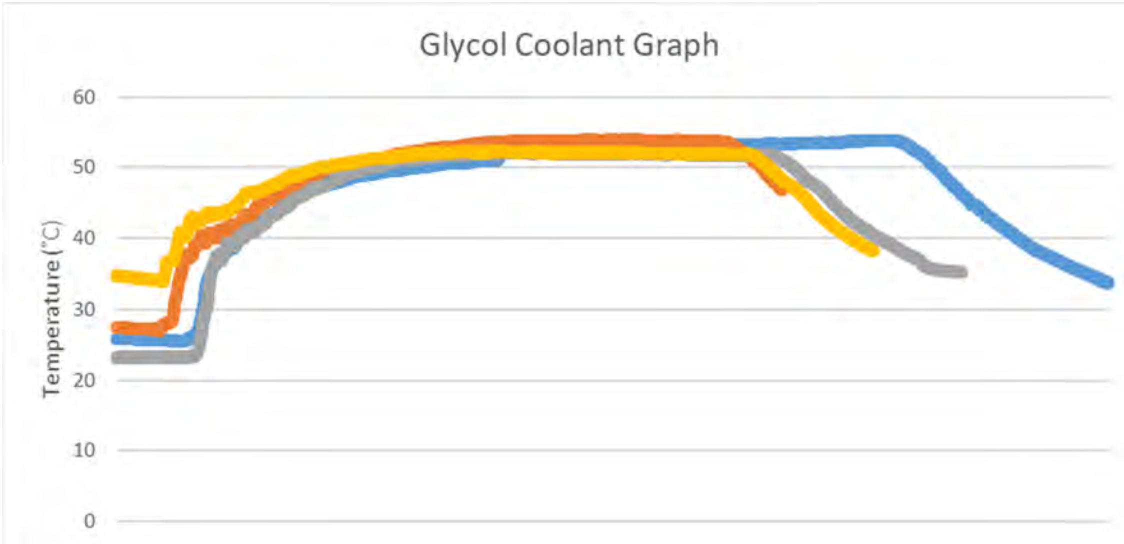


Figure 4-12: Glycol based coolant temperature profile across several prints

slowly to prevent boiling, but not enough as to drastically lower the overall temperature, the melting temperature would be reached. Unfortunately, as soon as the pump was permanently turned on, the temperature would aggressively reduce and settle below the melt temperature. One fix for this problem would be to develop a control scheme to balance between boiling and temperature reduction, but this was a much deeper problem that requires redesigning for better reliability.

Because aluminium is a very good conductor and the extruders barrel/cooler were made from one solid piece, when heat is transferred into one end of the system, the heat travels to the other very rapidly. This prevents a concentrated melt zone from forming before the cooling block would boil; the entire block, including the water-cooler, was heating up simultaneously. While a new design was in development a temporary fix for this problem was used for testing. This was achieved by replacing the water with a heavy concentration of glycol in car radiator fluid to boost the coolants boiling temperature to about 190°C. The tests were successful in reaching the melting temperature without boiling, but the coolant itself in a concentrated form was not as efficient at removing heat and cooling down again, so the coolant loop ran fairly warm as seen in Fig. 4-12. This provided enough cooling and system stability to run the process in 15-minute intervals, this enabled some tensile specimens to be printed successfully.

The first attempt at water cooling showed promising results in terms of extrusion capability and provides a good place to build from. The major improvement added to this new extruder is the addition of a thermal barrier which completely separates the water cooling block and the melt zone of barrel seen in Fig. 4-15. The material of the barrier is Teflon or PTFE (Polytetrafluoroethylene) which offers several beneficial properties: a high melting temperature of over 300°C, crucially, a

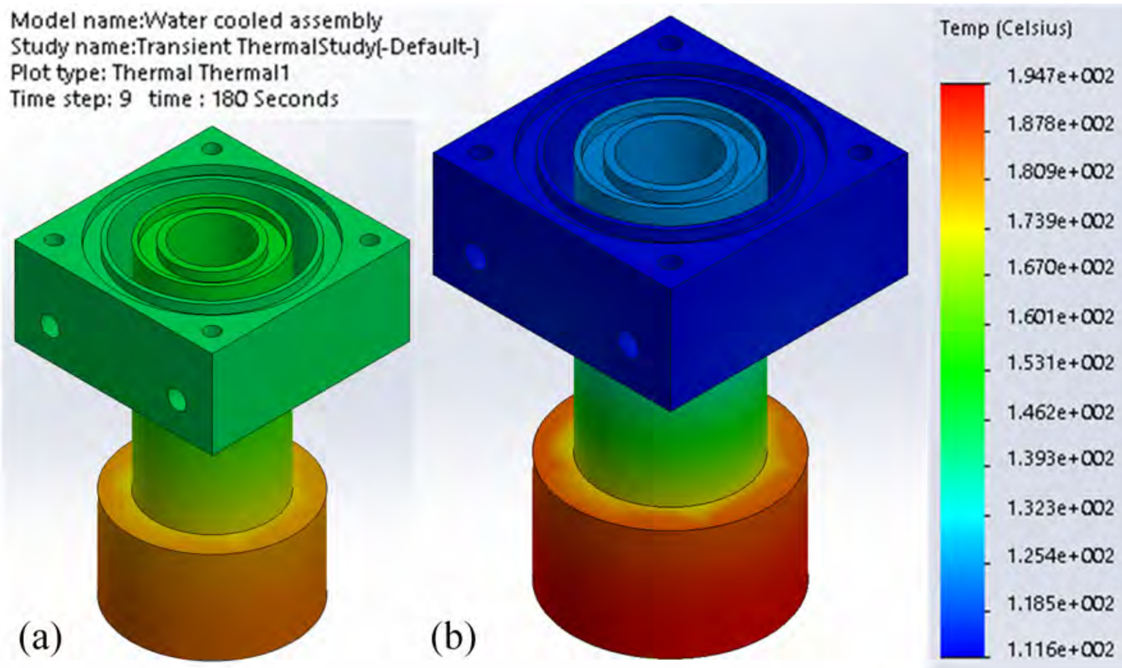


Figure 4-13: (a) Transient temperature study of the initial water-cooled block, stopped at 100°C in 180 seconds, (b) a static temperature analysis of the initial water-cooled block

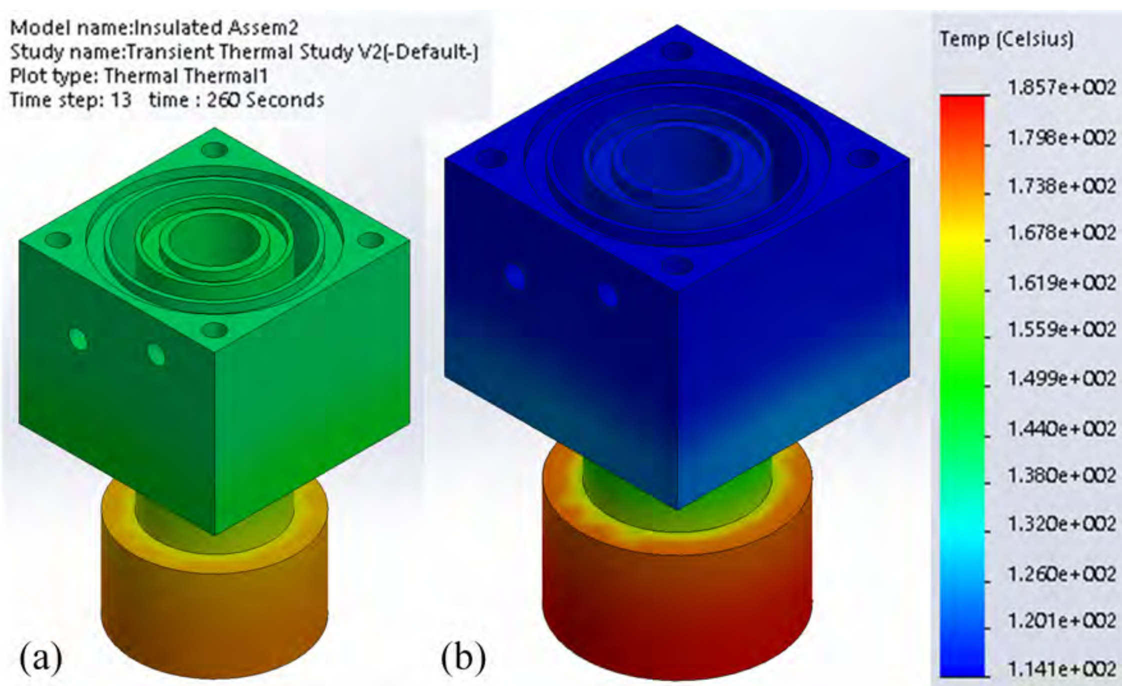


Figure 4-14: (a) Transient temperature study of the new water-cooled block, stopped at 100°C in 260 seconds, (b) a static temperature analysis of the new water-cooled block

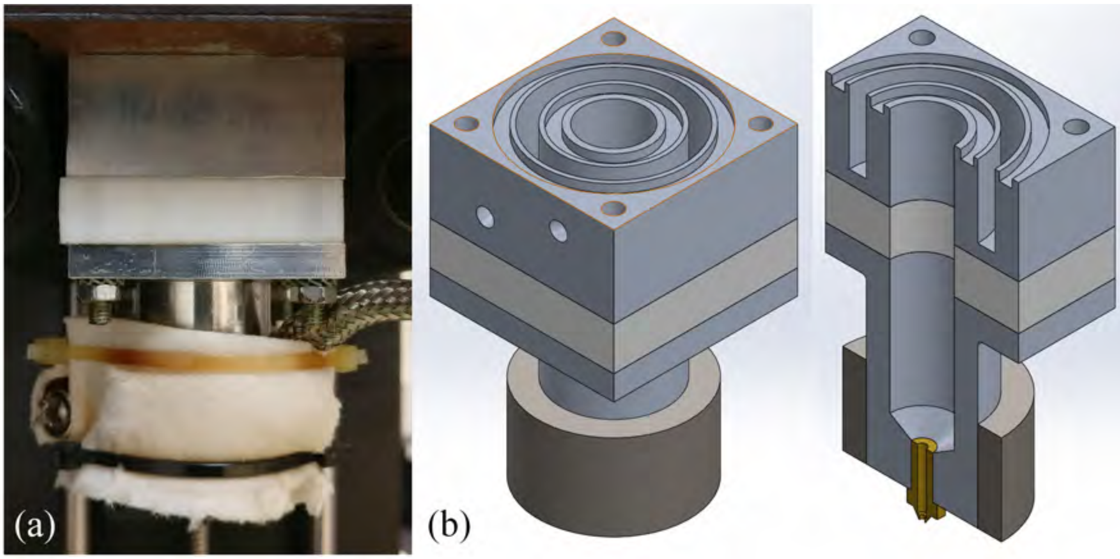


Figure 4-15: (a) PTFE thermal barrier water cooler, (b) SolidWorks model of the PTFE water cooled design

low coefficient of friction, and the biggest factor is its low thermal conductivity of 0.25W/mK compared to aluminium's 205W/mK [8]. To test the conductivity, a static and transient thermal study was conducted on each of the fluid cooled extruder designs seen in Fig. 4-13 and Fig. 4-14. The assembly contacts and materials were defined with the correct conductive values, with Thermal Grizzle high temperature thermal paste between the heating band and the barrel. It has a maximum temperture of 350°C and a thermal conductivity of 12.5W/mK. Estimations were made around the convection values of air conditioning and there was no water modelled in either simulation.

The results were promising with the new design showing a longer time for the cooling channel to reach the boiling point of water (100°C) Fig. 4-13(a) and Fig. 4-14(a). The biggest difference lies in seeing the end static result, the original model (Fig. 4-13(b)) shows the inner bore at around 130°C after 600 seconds which is where the boiling problems occurred. The new model (Fig. 4-14(b)) shows a cooler 114°C (although still above boiling range) around the cooling block, but what is interesting is the clear temperature change below the PTFE barrier proving its effectiveness.

Based on the heating and boiling problems presented in the first water cooled design, the second version developed uses a PTFE block as a barrier to solve these issues. Its properties help improve the operating process in a few different ways. Firstly, the melt zone becomes more defined as the barriers conductivity prevents a rapid transfer of heat. Secondly, the non-stick surface helps by defining a position along the barrel where the polymer sticks to the wall creating friction within the material. Lastly, the barrier does what it is intended to do, it slows the heat transfer from the barrel to the cooling block. It does it so well that water can now be used again without the risk

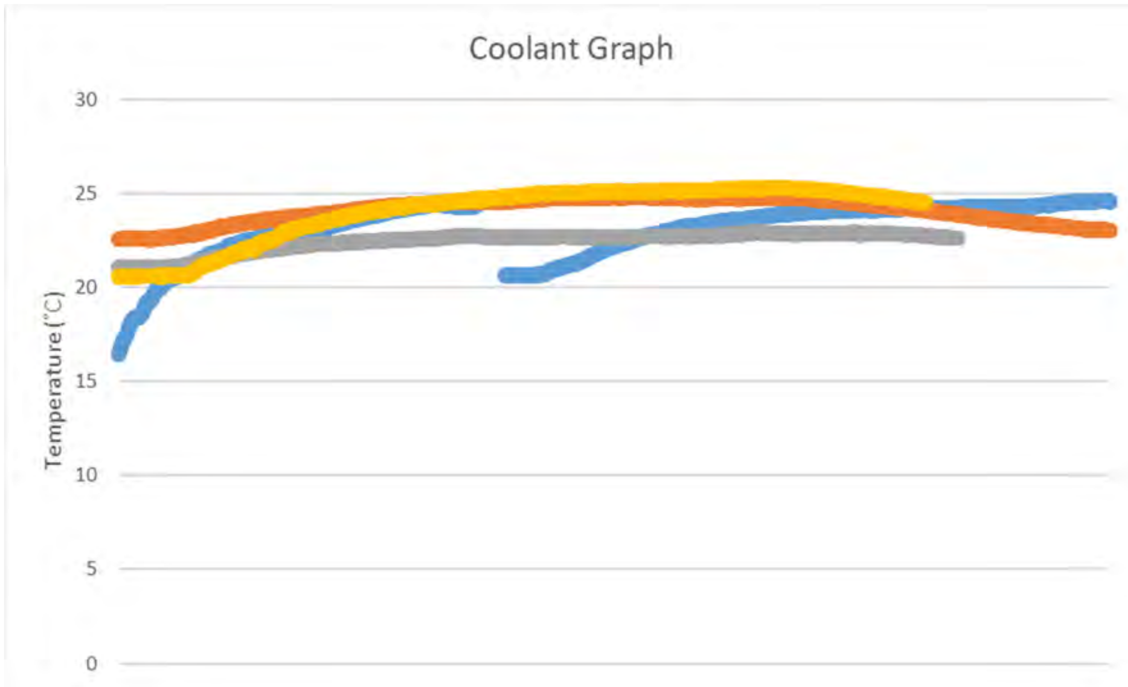


Figure 4-16: Water based coolant temperature profile across several prints

of boiling. During testing of this design, the efficiency of the cooling was improved greatly, and the water's temperature was able to be maintained at a much lower level during operation as seen in Fig. 4-16. Later on, to further assist with heat isolation, some ceramic insulation padding is wrapped around the heating band to lower heat transfer losses and further focus the melt zone Fig. 4-15(a). A visual representation of the heating, cooling and extrusion was captured using a Flir A615 thermal imaging camera. These images can be seen in Appendix A.

4.2.3 Barrel, Screw and Die Development

A screw extruder is commonly associated with large-scale devices that continuously extrude a bead of material for a range of different applications. These extruders are quite complex and must take into account many different factors, ranging from the properties of the polymer, the material feed, the temperate profile along the barrel, the pressures created and more. Out of all of these factors, the most important part of a screw extruder is the screw. The material process, from feeding into the extruder, to seeing the output extruded from the die, is handled by the screw. Typically, a screw's job in a continuous system is to convey the material through a plastication process. This can be as simple as a single compression zone, but could also be made up of many stages, such as mixing, devolatilization, compression and even decompression zones. These types of screw extruders are large in scale because it is more practical for the large outputs that they are designed for, and they quite often need bulky motor and gearbox assemblies to drive through the forces these systems generate.

In contrast, the design of this proposed extruder revolves more around miniaturising and simplifying the technology to the point where the entire 3D printing system is comfortable sitting in a desktop environment. The favoured screw extruder design that is widely used is typically setup horizontally and drives the material in a fashion relatable to the workings of an Archimedean screw. This extruder method relies on friction or drag to produce movement (Section 2.3.3 Fig. 2-11). A horizontal design, although possible, would be challenging and more complex to implement into a 3D printer's gantry like design. A different approach was chosen to minimise the extruders footprint by vertically mounting the extruder and utilising gravity as a means of assisting the transport of material. The shape of the material is not perfectly uniform; therefore, the flow is more unpredictable and can cause conveying inconsistencies. If this happens it can carry on through the process and potentially destabilise the output; the hopper and screw designs need to take this into account.

The graphs seen in Fig. 4-17 depict a general representation of the pressure gradients caused along each screw as the material flow generated is opposed by the die. The pressure graph shown along screw (a) has a distinct pressure gradient climb rapidly over the compression zone (L_{comp}). The total pressure calculation along the screw is the sum of the different zone pressure variations described by:

$$BackPressure = \Delta P_{feed} + \Delta P_{comp} + \Delta P_{meter} \tag{4.1}$$

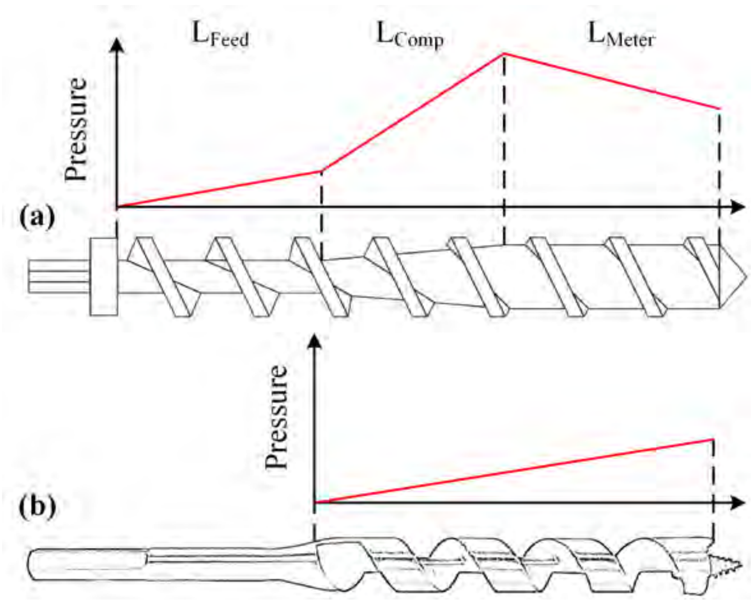


Figure 4-17: Visual pressure comparison between a multi-zone continuous screw and the no compression auger screw [14]

However in a small extruder intended for 3D printing the large output torque required by the drive motor to generate the necessary friction would not be suitable for the size and wight constraints. Additionally, the extruder for 3D printing needs to repeatedly start/stop and this can put a lot of stress on the drive motor. Therefore, a totally unconventional approach was taken by using a modified auger drill bit (Fig. 2(c)). This was done considering the fact that in our design the purpose of the screw was just to deliver the polymer to the heating zone and push the melted polymer through the extrusion tip. This method significantly reduces the torque requirement and stress acting on the drive motor. Lowering the required motor torque allows easy selection of the driver motor and leads to a lighter, more controllable system overall. Because a high pressure is not the aim of this design, the pressure capability of the screw can be reduced by removing both the compression and metering zones. Thus, the entire screw becomes one long feed zone represented by:

$$\Delta P_{feed} = \frac{dP}{dZ} L \tag{4.2}$$

with L being the length of the screw and dP/dZ being the pressure gradient over the length of the screw [14]. The result is in a much lower pressure represented graphically in Fig. 4-17(b). Since the pressure is directly related to the length of the screw, any length above a minimum value produces extrusion necessary for the printing process. Furthermore, as the pellets are drip-fed, the actual length of the screw that generates pressure is smaller than the total length. As a general

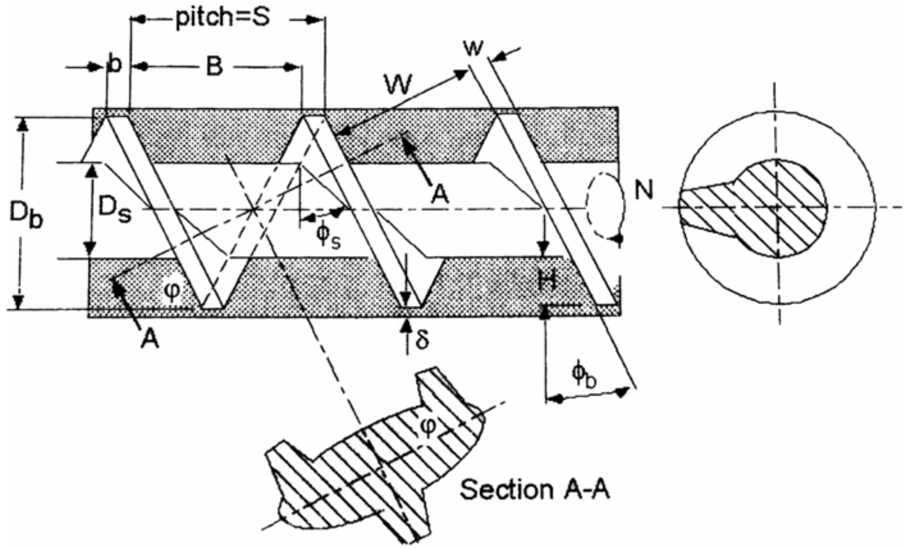


Figure 4-18: Screw geometries [57]

principle, if the screw does not extrude due to lack of pressure, increasing the pellet feed would increase the actual feed length of the screw and this will increase the pressure and the screw will start to extrude.

Extrusion is rarely developed to work with small scale systems. It may be because of their complexity, but all known sources that have developed miniaturised systems use a similar continuous compression designs [24, 32, 58, 1] with one patent pending design using a conical bore for one long compression zone [65]. Screw extrusion in large systems requires a lot of process knowledge, setup and control to monitor and maintain the output. Shrinking this type of system is not common knowledge and if done successfully, the information on how to do so is not typically disclosed. It is found that in using screw scaling rules that when shrinking a system down too far the dimensions start to make less sense [24], and the mechanical aspects generally need bulky equipment making for a slow undesirable 3D printing system.

There are many geometric factors in a screws design that affect the material process, these are things such as the clearance between the screw and the barrel, the flight angles, the channel depth and the different zones (Fig. 4-18). Some of the measurements for the screw used in the proposed design are seen in Table 4.1. The size of the gap between the screw and the barrel can help with maintaining melting temperature, but it is also attributed to how quickly the material melts. With an increase in clearance a reduction in melt rate can be observed, but it is not a critical factor if the solid material particles fed in are larger than the gap (it is true in this case). The melting of material generally starts to occur a few flights into the screw. This begins where the friction is highest around the barrels surface, which is why clearance is an important factor [57].

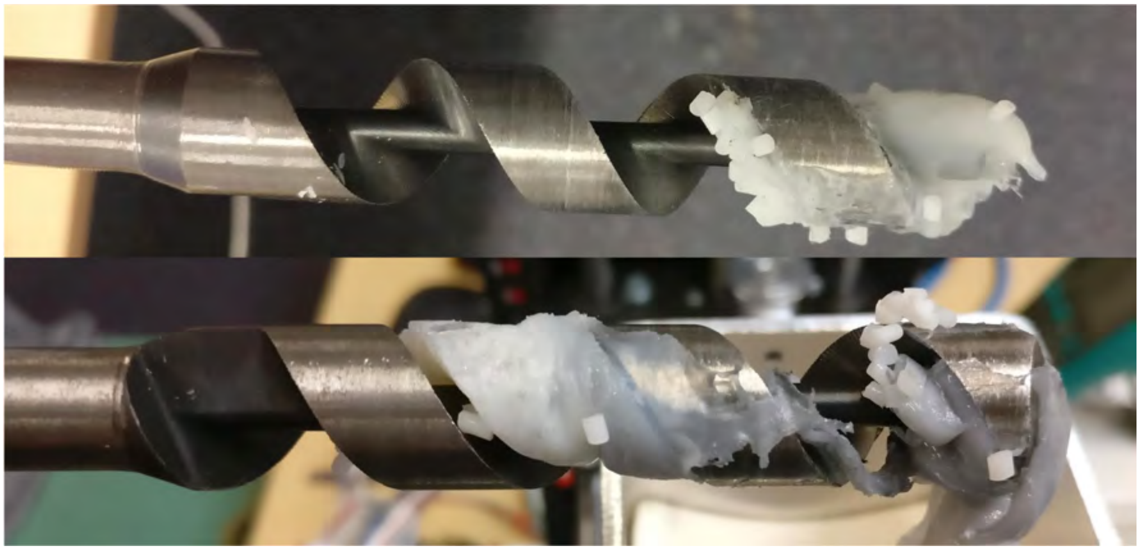


Figure 4-19: (Top) Isolated melt region with correct feed transport, (Bottom) Block occurred mid way down

These screw factors are usually referring to multi-stage screw designs where geometric profiles, angles and clearances are somewhat critical to transport, melt and pressure generation. The factors relating to friction, heat generation and conveying of particles do not apply as well to a varying discontinuous extrusion processes. Gravity has a specific role to play in assisting the feed of pellets into a screw's channel. For the particles to feed into the barrel, the channel needs to have a sufficient depth and/or pitch for varying pellet sizes to have unrestricted access. The proposed design has a vertically mounted screw, therefore the material conveying zone is critical in transporting the pellets into the melt region without blocking as seen in Fig. 4-19.

The extruder's aluminium barrel provides quick, reactive heating properties, as well as fast cooling properties. The cooling development is described in the previous section, but along with the changes to cooling came the change in barrel length and flow channel. The original extruder design had problems with fluctuating output which was partially caused through poor cooling, but it was also due to the sharp change in geometry at the end of the barrel (flow channel) shown in Fig. 4-20(a). In the later designs, the flow channel was made to be more gradual to reduce any dead spots and support flow into the extrusion tip which had also been shrunken to a more standard M5 size. The chosen screw was a 15mm auger drill bit, which was used off the shelf at full length hence the longer barrel in Fig. 4-20(a).

Because the screw does not have a compression or metering zone, it would be more efficient if the screw were much shorter and the cooling was much more effective. The change from (a) to (b) in Fig. 4-20 was an attempt to focus the melt zone with more aggressive water cooling and to shrink down the extrusion screw to 85mm along the helix section. The concept showed promise,

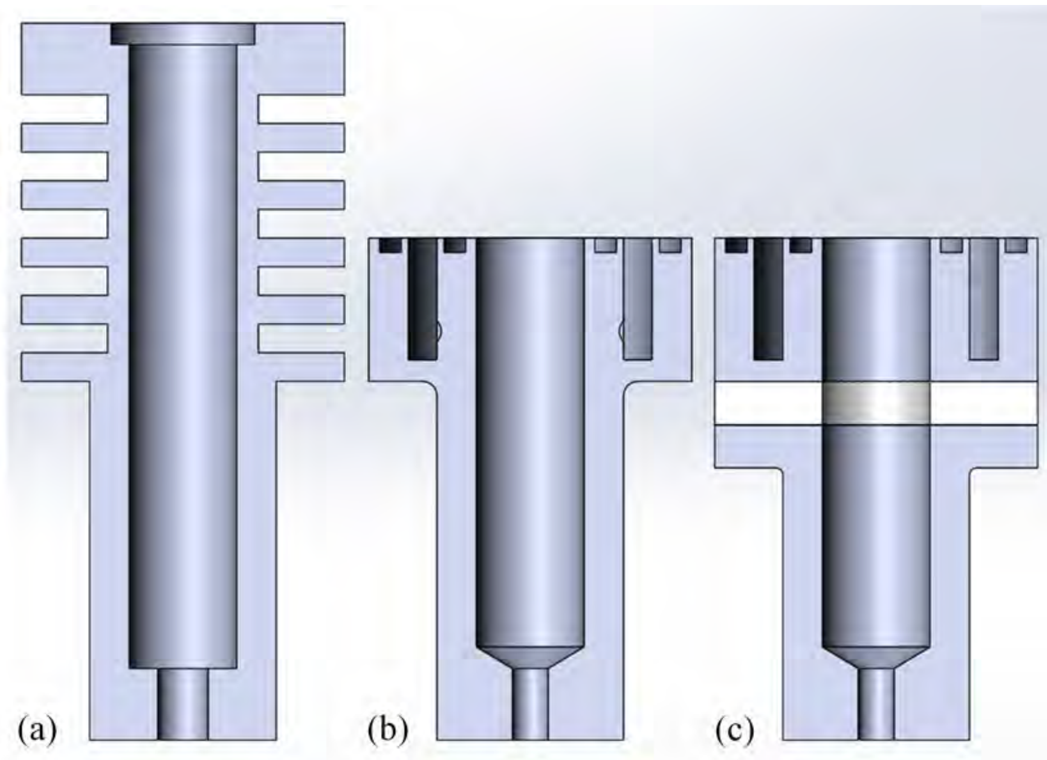


Figure 4-20: (a) Initial air-cooled extruder design, (b) first water-cooled extruder design, (c) latest water-cooled extruder design with a thermal barrier

but cooling was not effective enough, so an improved version was developed seen in Fig. 4-20(c), producing a concentrated heating zone of approximately 30mm in length. The heat up and cool down times related to aluminium's thermal conductivity are very quick, although it is quite a soft material, meaning that wearing along the barrel wall can be quite significant, and the clearance could result in output fluctuations sooner than other materials.

Table 4.1: Extrusion screw properties based on the proposed extruder

Screw Properties	**Values**
Flight Clearance	0.03 ± 0.02mm
Channel Depth	5mm
Screw Length	85mm
Channel Diameter	15mm
Screw Pitch	28mm
Channels	Single
Drive Torque	5Nm
Material Density	1.25g/cm^3

4.3 Measurement, Communication and Control

The implementation of control in any extruder system is one of the most important aspects. Sensors common in more complex extrusion systems monitor screw speeds, temperatures along the barrel, pressure, power consumptions and, in some cases, vacuum pressure. In more complex setups, if something were to unexpectedly go wrong and the output veers off course, the feedback from monitoring the system can provide valuable insight as to what went wrong or narrow down the cause of the problem. Without monitoring the process, the only way you could tell if everything is operating correctly is to look at the output. If something is wrong, it would be too late to determine where the problem originated. The most important parameters for an extruder to maintain a consistent output are the temperatures along the barrel and the pressure generated for extrusion. These are important because a system may have several factors such as viscosity which operate within an optimal range. For example, if the temperature goes above or below the ideal melt temperature, then the viscosity of the polymer will change causing a pressure drop and fluctuations in the output.

As previously outlined in Section 3.1 there are several types of software used in controlling everything from how the g-code parameters are generated, to how the system is monitored, to defining the control of mechanical and hardware aspects of the platform. The platform is designed and made with parts that are widely available and commonly used in the open source community, therefore they are to be compatible with openly developed hardware. The mixture of open source software and hardware allows the full advantage of the customisation without being blocked out by proprietary restrictions and licensing. The primary piece of software is Slic3r. This is simply the way in which a 3D model can be converted into layers and step by step instructions for the printer to follow. This software allows refined control over many factors that go into how the printer operates and is the main piece of software used in tuning the process behaviour. The g-code or instructions are generated based on the different parameters defined in the slicing configuration menu. These cover everything; from layer dimensions, to speeds and thicknesses of different processes, to support generation, cooling effects and even platform adjustments.

The second piece of software is called Pronterface, it is a graphical user interface (GUI) between the printer and the PC. This software connects to the printer over serial communication which it uses to relay the g-code instructions to the printer, but also receives feedback from the printer's temperature sensors (Table 4.2). This program is used in the start-up procedure of the printer (Fig. 4-21), calibration of the platform and used as a general controller to aid in tasks such as material changeover and maintenance. The third piece of software is called Marlin. It is the brains of the printer running on a Ramps 1.4 control board. Its job is to receive the g-code commands and control

Table 4.2: Common RepRap printing g-code commands [6]

Common G-Code Commands	What They Do
G0 - G1	Move
G92	Set position
M101 - M102	Turn extruder on (Forwards - Reverse)
M103	Turn extruder(s) Off
M104	Set extruder temperature
M106 - M107	Turn fan (On - Off)
M109	Wait for extruder temperature to be reached

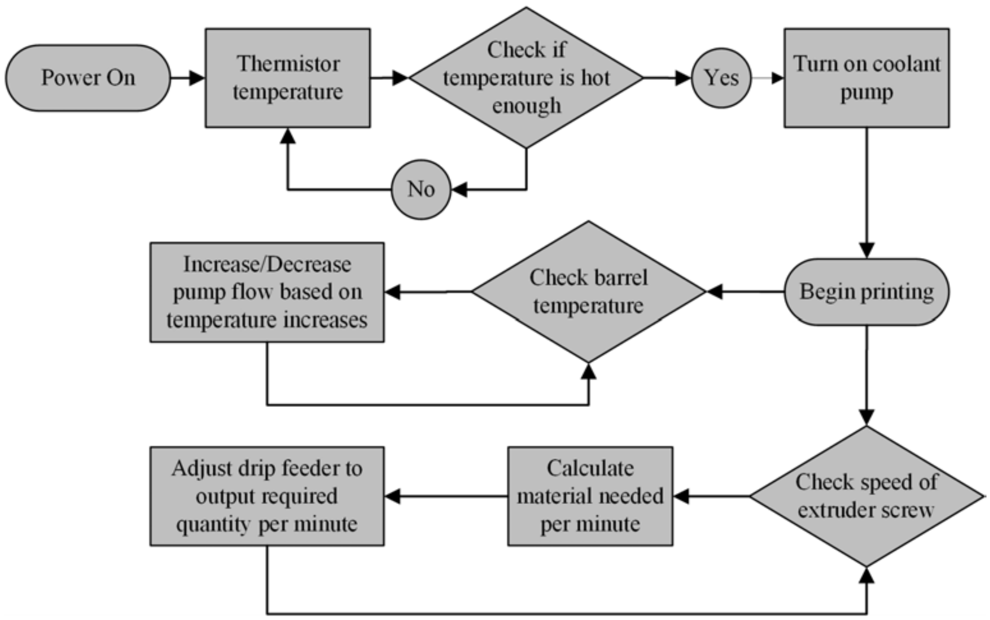


Figure 4-21: Extruder system process

the printer accordingly. Inside Marlin there is a configuration file that allows the definition of your printing system, from sensors, to control measures, to mechanical features, to levelling and even safety precautions.

Most of these measurements are fundamental to the proper operation of a complex large-scale extruder. When developing an extruder on a small scale with mechanical aspects that are not as refined and accurate, it becomes a lot harder to implement these measurements. Compromises were made as to which measurements are necessary to produce a reliable and consistent process. There is delicate balance between the speed of the screw, the temperature inside the barrel and the quantity of material being fed into the hopper. As this extrusion system does not use a conventional screw, it is not relying heavily on polymer shear or a compression zone to melt the material. Therefore, the screw's focus rests on conveying the material into the band heated melt zone and pushing it out of the extrusion tip.

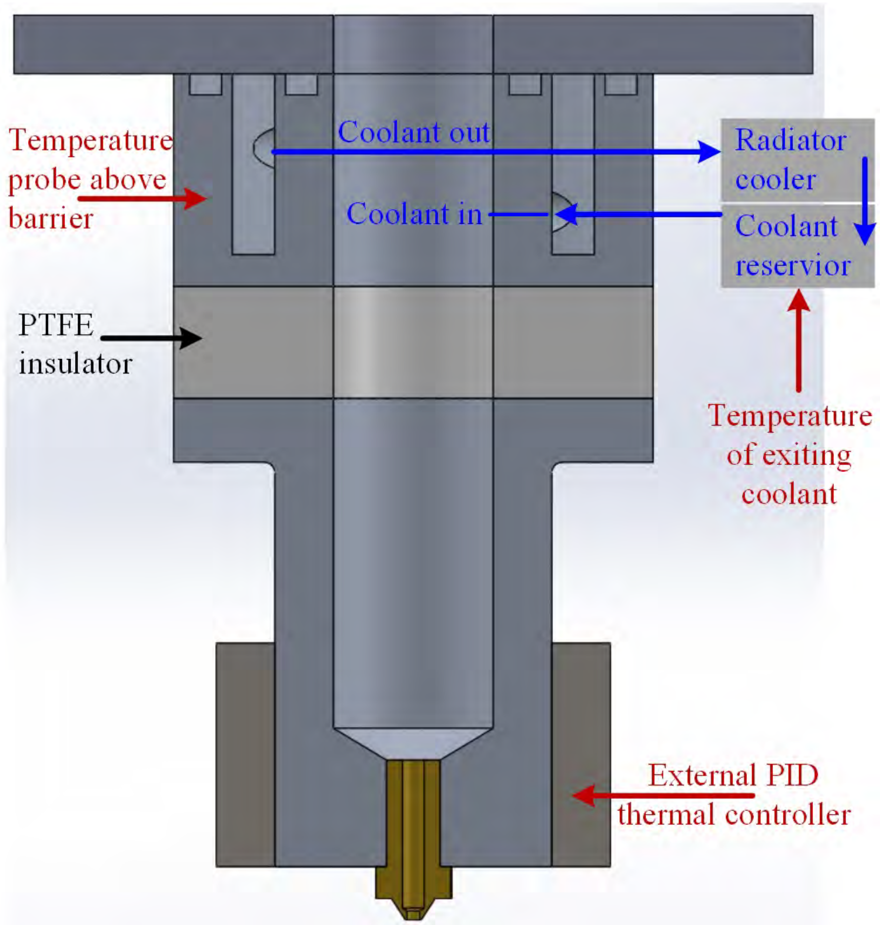


Figure 4-22: Extruder sensor and monitoring locations

With the idea of conveying the gravity fed pellets in a small extruder, the pressure generated will be quite small in scale and quite erratic through printing behaviours. The inclusion of a pressure sensor would almost be of no use to the printing process, because acting on fluctuations caused by printing behaviour could result in wrongful actions. The use of a pressure transducer was therefore not implemented into the design. To reduce inconsistencies, the screw speed is strictly set during printing using Slic3r software to generate the g-code output. This allows the pellets to be conveyed in a controlled manner; additionally, by monitoring and controlling the temperatures, a large improvement can be seen during testing.

At the same time instructions are being transmitted to the printer, there is also feedback being received. The response is used to monitor the system and make sure that the process is running within parameters. One feature that heavily impacts this system is the heat, therefore temperature control is necessary to help reduce potential fluctuations in viscosity. There are two sources of heating on the printer, the main one is a thermal band around the end of the extruder, and the second is the heated printing platform. The temperature of the bed is measured with a thermistor connected to the printer's controller, whereas the band heater has an internal thermocouple that is connected to an external controller. The external controller is a Watlow EZ-ZONE PID controller which not only monitors the temperature, it also has an internal relay that is PID controlled to maintain the desired temperature.

The coolant channel around the barrel and the circulating coolant are also monitored for temperature as seen in Fig. 4-22. These temperatures are taken using platinum (PT100) resistive temperature detectors (RTD), one on the coolant exiting the reservoir and the other on the external surface of the coolant block. These sensors are connected to an external Arduino based controller along with the drip feeder which communicates over serial to a custom interface as seen in Fig. 4-23.

As the cooling system progressed from air to water cooling, the water reached boiling temperature much faster than expected (discussed in Section 4.2.2) and turning the pump on forced the extruders temperature to stabilise below the melt temperature. One of the potential fixes was to implement a control system for the coolant pump flowrate to restrict or increase flow as needed, both preventing the coolant from boiling and also to stop excessive heat from propagating upwards. The controller relied on a Fuzzy Logic based approach. It has set boundary conditions, taking into account the coolant and the barrel temperatures Fig. 4-21. This control method was never fully implemented as a better design was made, but the interface provides a means of feeder control and temperature data collection. The improved extruder design with a PTFE thermal barrier helped to further isolate the heating zone, and by doing so it relieved the pumps cooling job, meaning the pump controller no longer needed developing.

Through the Slic3r configurations a fixed screw speed can be applied to all printing actions. This fixed speed paired with controlled temperatures can convey material into the melt zone and extrude a bead of material at a constant rate. By filling up the hopper manually it can cause heating to become inconsistent and the pellets can start to stick together resulting in intermittent or no feeding. For the extrusion output to be controllable and consistent, the infeed of material must also be controlled. It was tested and observed that in smaller quantities the process remained in a stable state, maintaining a balance throughout multiple test runs. A drip-feeding (starve feeding) hopper was implemented as a more permanent solution as a means of control over the feed quantity. To maintain the correct feed rate, a controller (Fig. 4-24) and interface (Fig. 4-23) were designed to make adjustments for rough reliability in feeding material at set intervals. The quantity of material is calculated over time to roughly match the amount of material being extruded during printing.

The external Arduino controller as seen in Fig. 4-24, manages the feeder's DC motor and the two temperature sensors for coolant. The printed circuit board (PCB) was designed as a single layer

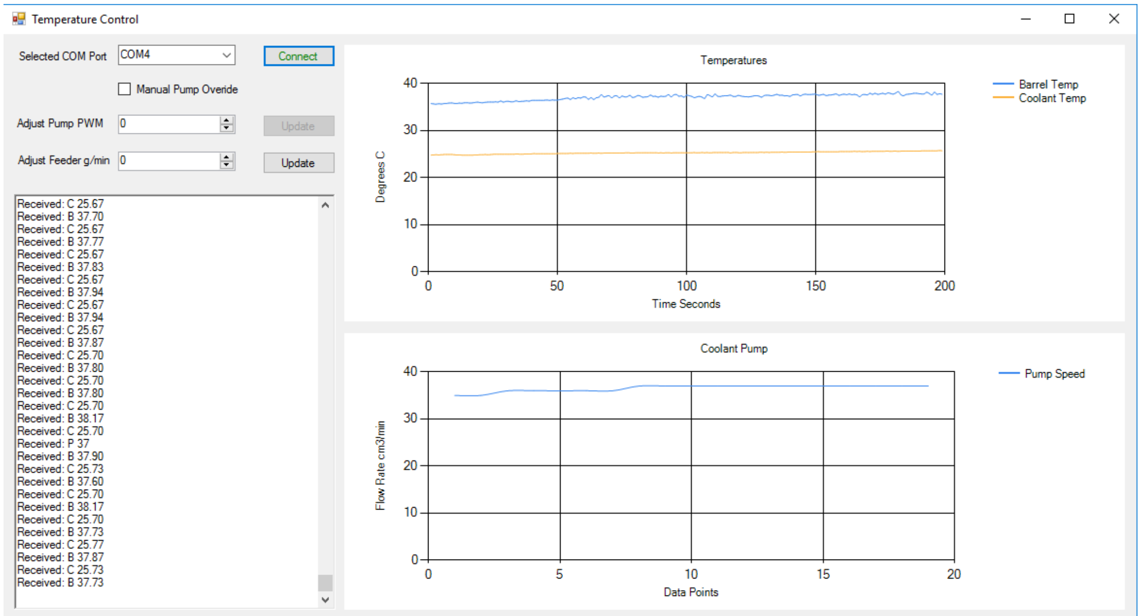


Figure 4-23: Control interface for the temperature and feeder access

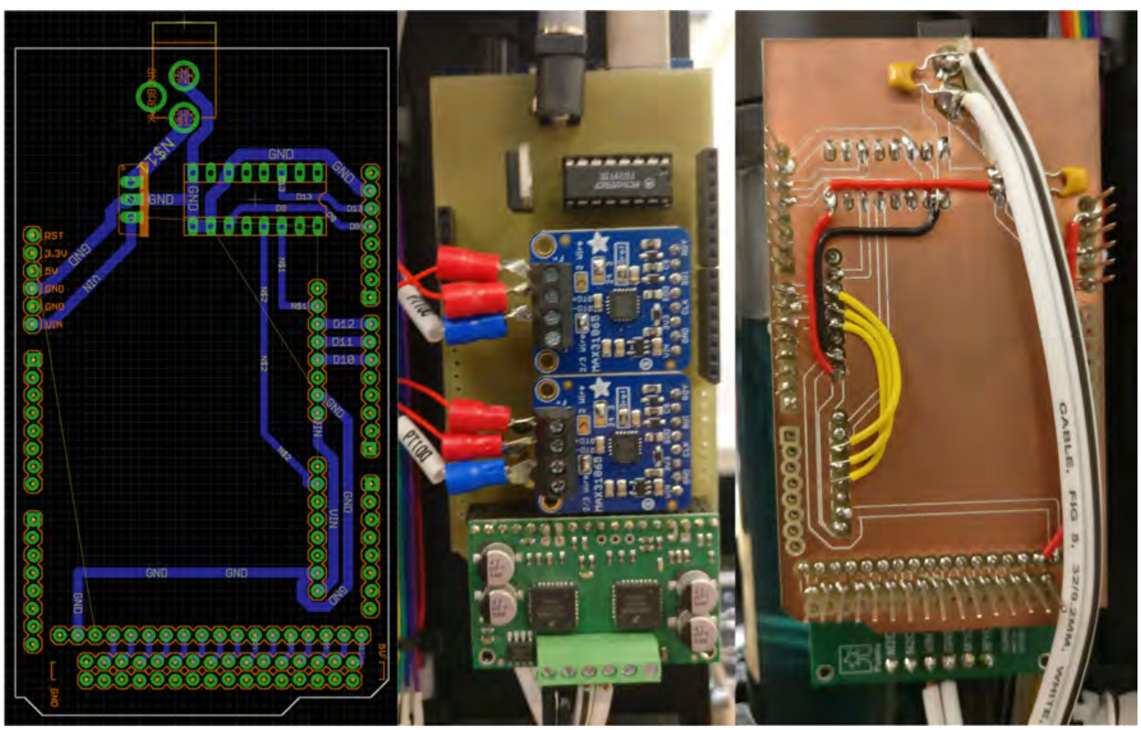


Figure 4-24: (Left) Eagle designed controller schematic, (Middle) top view of controller containing the interfaced electronics, (Right) underside of board showing the deliberate jumper wires

```
void loop() {
  currentMillis = millis();

  if (Serial.available() > 0) { … }

  //if feeder is running and stuck, then reverse
  if ((currentMillis - encoderStallCount) >= 1000 && motorDirFlag == 1 && feederFlag == 1) {
    reverse();
  }
  //if reverse time is finished, change back to foward
  if ((currentMillis - reverseTimer) >= 200 && motorDirFlag == 0) {
    reverse();
  }
  //change between sensors to read both
  if ((currentMillis - tempSensorTimer) >= 500) {
    tempCalculation();
  }
  //check pump speed versus current system temperatures
  if ((currentMillis - pumpCalcTimer) >= 10000) {
        pumpCalculation(avgTemp);
  }
  //if feeder has been on for required interval, turn off
  if ((currentMillis - feederTimer) >= (feederOnTime * 1000) && feederFlag == 1) {
        enableFeeder();
  }
  //if feeder has been off for calculated interval, turn on
  if ((currentMillis - feederTimer) >= feedTime && feederFlag == 0) {
        enableFeeder();
  }
}
```

Figure 4-25: Main controller loop running based on a timer counting routine

using Eagle, this meant some of the pins had to be manually routed underneath to avoid clutter. The DC motor driver is a Pololu Dual MC33926 (green board in Fig. 4-24(Middle)) which could easily handle the 12V input at 2.5A. It also has PWM control, reversal and enable capabilities. The reason for having a dual driving DC motor driver was for simultaneously controlling the coolant pump speed and the feeder.

The two PT100 RTD temperature sensors are connected to MAX31865 amplifier circuits from Adafruit seen as the blue boards in Fig. 4-24(Middle). The temperature sensor boards have their own software library which made the readouts somewhat difficult to deal with, the problem being that only one board can operate with the library at any given time. The solution was to trick the system into thinking it was using one board by running the boards in parallel. Both boards share the SDI, SDO, and CLK pins but the CS (Chip Select) pin of both sensors pass through a multiplexor. The CS pin can be used like an enable/disable option to define which sensor is being read from. Lastly there is a 5V regulator to step down the 12V supply to power the logic for each of the chips as well as the Arduino itself.

The program running on the controller can be broken down into several sections: the feeder speed and control, the temperature calculation and the pump speed calculation, but due to the success of the extruder developments, this was not completed. These functions are running off

```
if (Serial.available() > 0) {
    String cmd = "";
    double cmdNo = 0;
    while (1) {
        char c = Serial.read();    //reads first character
        switch (c) {
            case 'M': { … }
            case 'P': { … }
            case 'F': {
                delay(10);
                while (1) {
                    c = Serial.read();
                    if (c == '\n' || c == '\0') {
                        cmdNo = cmd.toDouble();
                        Serial.print("Previous Rate: ");
                        Serial.println(rate);
                        Serial.println("Return F: " + String(cmdNo));
                        rate = cmdNo;
                        feederSpeed(rate);
                        break;
                    }
                    else {
                        cmd += (char)c;
                    }
                }
            }
            break;
        }
        if (c == '\n') break;
        if (c == -1) continue;
    }
}
```

Figure 4-26: Serial reading function within the loop to detect incoming instructions

timers to essentially multitask and avoid disrupting the entire program with delays as seen in Fig. 4-25. The main loop of the program continuously runs and counts up a timer 'currentMillis'; this timer is used as a reference to trigger functions. If a function has finished, the timer relating to that function is reset by setting it equal to the main reference timer. This way, all functions are both independent from one another, there are no delays to the program and all act in accordance to the same reference point.

Inside the main loop is a function waiting to receive a message over serial from the control interface Fig. 4-23. If a number is typed into the GUI (e.g. feeder speed) and the update button is pressed a string containing the number is sent to the control board with an identifier in front (M, P or F). This serial event function is triggered and the first character (the identifier) is read from the string. This is then compared to a switch case: 'M' for toggling manual operation of the pump speed, 'P' for actually changing the pump speed, and 'F' for updating the feeder speed manually. In Fig. 4-26, the feeder case 'F' is shown, inside this, the next character following the identifier is read in. All characters read inside the switch case are checked to see if they are a null or new line character. If this check comes back true, then the serial message has ended and the collected transmission is acted upon accordingly. If not, the character is appended to a string called 'cmd'

```
void feederSpeed(double feedRate) {
        double eventMin = feedRate / 0.18;
        double interval = 60 - (eventMin * feederOnTime);
        feedTime = (interval / eventMin) * 1000;
}

void encoder() {
  //Need to count the encoder steps to tell if it stops
  encoderStallCount = currentMillis;
  if (digitalRead(encoderA) == HIGH) {
    encoderCount = encoderCount + 1;
  }
}
```

Figure 4-27: Feeder speed function and drive motor encoder interrupt function

and the next character in the transmission is checked.

The feeder is divided up into several different functions, the feeder's speed calculation, encoder counter, feeder enable and feeder reversal functions. The feeder speed (Fig. 4-27), is calculated based on the number of pellets output by the feeder screw in one revolution, as well as the amount of time it takes to complete one screw revolution. Firstly, a separate feeder circuit was designed to control the speed through PWM manipulation of the drive motor. This was successful to the extent where speed control was achieved, but the extruders output required a speed that was too low to produce sufficient torque.

This current feeder speed function is used to determine how often the feeder needs to turn on inside an arbitrary time of one minute. Each time the feeder is turned on, it is at full power and is only on for one revolution. By knowing approximately how much material comes out of one revolution, and how long the revolution takes, the calculation of how much time passes between occurrences can be worked out. By doing so, the drive motor is always driving at full power and the quantity output over time can still be controlled. The function reads in the 'feedRate' which is the required grams per minute that is changeable by the control interface. This is then put through a calculation where the quantity is divided by the approximate weight of pellets that is output in one revolution (0.18g). This is to find the number of screw revolution events that are needed to meet the desired quantity. Next, the calculation multiplies the number of events by the time it takes for a single revolution (approximately 1.6 seconds) and then takes it away from one minute to find out how much time is left to work with. The final stage is to take the remaining time and divide it by the previously calculated number of events, this gives the length of time in-between feeder events which is set to a timer to spread them out.

The encoder function is set to a hardware interrupt pin to register every rising edge of the encoder pulse. This provides feedback from the DC motor to let the system know if it is running correctly or has jammed up. This is done by setting a timer while the motor is enabled and if the

```
void enableFeeder() {
        if (feederFlag == 1) {
                digitalWrite(enablePin, LOW);
                feederFlag = 0;      //Feeder is stopping
                feederTimer = currentMillis;
                reverse();      //reverse to clear any potential blockage
        }
        else if (feederFlag == 0) {
                digitalWrite(enablePin, HIGH);     //enable feeder
                feederFlag = 1;      //Feeder is running
                feederTimer = currentMillis;
                //encoder();    //reset stall timer to say it wasn't stalled the entire time
        }
}

void reverse() {
    //Flag/direction returns to 1 when reverse timer has passed
    if (motorDirFlag == 1) {
        motorDirFlag = 0;         //Motor is reversing
        reverseTimer = currentMillis;
        digitalWrite(motorDirPin, HIGH);
        digitalWrite(enablePin, HIGH);
    }
    else if (motorDirFlag == 0) {
        motorDirFlag = 1;         //Motor is foward
        //encoderStallCount = currentMillis;
        digitalWrite(motorDirPin, LOW);
        digitalWrite(enablePin, LOW);
    }
}
```

Figure 4-28: Feeder enable/disable function and the feeders reverse function

motor's encoder counter is increasing, then it confirms that the motor is turning. This was needed for the original drip feeder design (Fig. 4-27) that experienced severe jamming problems.

The 'enableFeeder' function does exactly what it says, when called it checks a flag to see if it on or off (Fig. 4-28). If it is off, the DC driver pin is enabled turning the motor on, the running flag is set to high and the run timer is zeroed. If the motor is already running and the timer is finished, the driver pin is disabled, the run flag is set low, and the timer is zeroed again. Every time the feeder has finished running, the reverse function is called. The reverse function was originally implemented to be called by the encoder stalling. This was changed because the encoder became faulty and an updated feeder was made that had no trouble with jamming. If something does arise, the reverse function is called every time the motor comes to a stop. By doing so it does affect the output of the following revolution. This was adjusted for by reducing the feeder output per revolution from 0.2g to 0.18g. The motor is run in reverse in the same way as forward except it has an additional step of setting the DC drivers motor direction pin on and off.

The final important function in this program is 'tempCalculation' as seen in Fig. 4-29. This essentially reads each of the two RTD temperature sensors and relays the data to the GUI interface over serial. From the main loop, the tempCalculation function timer is set to 500 milliseconds (0.5 seconds) and because there are two sensors being read one at a time, together the readings occur

```
void tempCalculation () {
    static int index = 0;
    if (tempSensorFlag == 1) {
        digitalWrite(tempSwitch, LOW);
        digitalWrite(CS, HIGH);
        identifier = "B ";      //Barrel
        tempSensorFlag = 0;
    }
    else if (tempSensorFlag == 0) {
        digitalWrite(tempSwitch, HIGH);
        digitalWrite(CS, HIGH);
        identifier = "C ";      //Coolant
        tempSensorFlag = 1;
    }
    double sensorTemp = max.temperature(100, 430.0);
    Serial.println(identifier + String(sensorTemp));
    tempSensorTimer = currentMillis;
    digitalWrite(CS, LOW);      //Setting the CS low between changes to avoid random noise

    if (tempSensorFlag == 0) { //only reading Barrel Temperature
        if (index >= 4) {
            index = 0;
        }
        avgBarrelTemps[index] = sensorTemp;
        index++;
    }
}
```

Figure 4-29: Temperature calculation function using an open source library

at one second intervals. Progressing through the function there is an if statement that checks a flag (tempSensorFlag) and determines which sensor to read, the inside of both statements are basically the same. The 'tempSwitch' pin is written either low or high to toggle the multiplexor and select which of the RTD chip select pins is to be used. The chip select pin is then written high to enable the desired temperature sensor chip. A character identifier is assigned to the string 'identifier' in accordance to the barrel or coolant temperature sensor, and the sensor flag is toggled for the following passthrough. Once the selected chip is active, the temperature is read off by calling the 'max' library which takes the resistive sensor value and compares it to a 430-ohm reference resistor to calculate the correct temperature. That temperature is then added to the identifier string and sent over serial to be displayed on the GUI and stored as data in a separate text file. The temperature sensor timer is zeroed, and the chip select pin is set low to prevent random noise from ruining a temperature value.

Below where the chip select pin is set low in Fig. 4-29 shown as 'digitalWrite(CS,LOW)', there is an array of barrel temperature readings that continuously writes over itself. These values were to be used in a pump flow calculation function. This was where an average temperature value is needed to remove any possibility of stray fluctuations, hence the array of temperatures continuously updating to be used as a gradual reference. The pump was to be controlled via PWM through the dual DC driver. The flow rate was to take into account both the coolant block temperature and the coolant passing through the coolant loop.

4.4 Limitations and Improvements

The addition of a Teflon thermal barrier to the extrusion block greatly improved the efficiency and performance of the extrusion process. But the effect of slowing down the transfer of heat through the walls of the extruder barrel into the cooling block is only part of the problem. The second part is the heat rising up through the screw. During long prints, it transfers all the way up through the extruder to heat up the gearbox and motor itself effecting the efficiency. Worse than that, it affects the polymer inside the hopper, as the pellets fall from the feeder into the main hopper they can end up sticking to the screw causing a blockage. To prevent this screw cooling measures should be implemented; obviously the screw is too small to use internal liquid cooling. Something along the lines of wrapping a coolant loop around the neck of the screw, allowing it to slip on its surface could be effective. A second method could be to add air cooling fins to the screw itself.

On a different note, the material that the barrel of the extruder is made from is aluminium. Though this is a great thermal conductor and allows a quick start-up time it is also quite soft and loses heat fairly quickly as well. The softness of the material walls inside the barrel can cause contamination as the frictional forces created during extrusion can cause wear, plus any deflection in the screw can cause it to shave off unwanted particulates. Another material like steel could help in keeping the heat in longer and create a more stable process temperature, it is also stronger than aluminium meaning reduced wear and tear. This could also open up possibilities to add an inner surface coating on the barrel wall to further increase the toughness.

There could be improvements in terms of extruder start-up times and knowledge around what is happening inside the extruder. It could be beneficial to include a pressure transducer to help determine if the correct pressure is obtained before starting the process, or maybe even to gain a better idea of what is happening during printing. It could also provide valuable feedback in controlling the feeder during printing. If this is not possible, another approach could be to use some form of vision processing in determining if the output extrusion is of adequate thickness and diameter, the result of the correct extrusion pressure.

Chapter 5

Mechanical Characterisation and Optimisation

5.1 Print Consistency and Calibration

Once the platform had been assembled to working condition, calibration of the axes was carried out in the control software Marlin. Marlin provides accurate control over defining the operational parameters of the printer. The x, y and z axes were configured for 1/16 microstepping and the steps were finely adjusted by inputting an estimated value (steps per mm) and checking it against the resulting movement. Adjustments to fine tune the travel can be made using the following equation:

$$NewStepsPermm = (ExpectedTravel(mm))/(ActualTravel(mm))OriginalStepsPermm \qquad (5.1)$$

Once the calibrated values were set, the printer's performance was first estimated in Slic3r by setting initial layer height, nozzle size and infill settings. The print speed was fixed to the output of the 3rpm DC motor at an estimated 7.5mm/s, the layer height was set to 0.3mm using a 1.2mm nozzle, the fill density was set to 20% at a 45° angle, and the extrusion temperature was set to 195°C. The calibration tests were first run using Harakeke flax fiber composite blend with PLA to see if the design was plausible.

The results seen in Fig. 5-1 revealed issues with having a layer height that was too thin, this

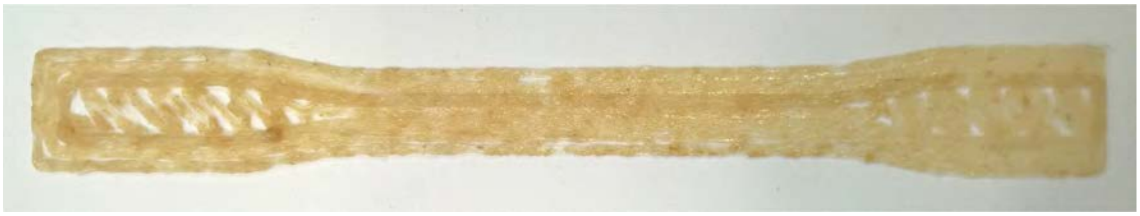


Figure 5-1: First test print attempt carried out using a PLA and flax fiber blend

Figure 5-2: (Left) Increments in layer thickness, (Right) Refined parameters

created a smearing effect with increased layer height. Having a 20% infill did not help with refining the process, therefore it was changed to a solid fill to better see progress. The print speed in relation to the DC output was slightly too slow and was increased to 8mm/s.

After several more refinements in the printing parameters, the results provided insight into how different parameters affect the output and in what ways. As testing proceeded, the layer height, printing speed, and extrusion width were manipulated in an attempt to improve the aesthetic quality and consistency of the prints. The most persistent problem with this printer was the nozzle digging into the layering as more and more layers were added. The solution to this issue was to increase the layer height, thus reducing the number of layers and increasing the step size to reduce the drag between each layer Fig. 5-2.

What was observed throughout each test run was the difference between the thickness being extruded out of the barrel compared to the nozzle size. The settings were continuously changed back and forth to find the optimal settings. The reason why the extrudate was so inconsistent was later found to be the result of having a high moisture content. To obtain an output of the correct dimensions, the parameters were set to approximately 3mm extrusion diameter and a layer height of about 0.7mm. Furthermore, to reduce the nozzle drag, the infill print speed had to be increased to 8.5mm/s as the slicing software is expecting the drive motor to accelerate differently.

Table 5.1: Different printing parameters between materials to achieve accetable results

	PLA	PLA	Flax Fiber Blend	PET
Print Speed (mm/s)	10	12 - 30	10	10
Nozzle Size (mm)	1.5	0.8	1.5	0.8
Extrusion Multiplier (%)	380	400	400	1400

As a result of these tests running flax fiber, a new batch of virgin PLA was received to continue refinement of the extrusion system. The same parameters were initially run to see where the system stood, and it was immediately apparent that the motor needed more control than just an on-switch. The change was made to swap over to a NEMA 17 stepper motor which was compatible with the current control board. When it came to calibration, the screw extruder was far more of a challenge as the software is expecting a filament extruder and only accepts a value for steps per millimeter. The steps per rotation of the extruder screw did not correspond to the material output. Only a weak relationship between the drive motor steps and output speed could be made before a more consistent feeding system was implemented.

The drive motor is a geared stepper motor with a 19:1 ratio which calculates out to be 3800 steps per revolution (200 steps/rev x 19:1 ratio) which is taken into account to find the relationship between steps and quantity extruded. The original estimate was approximated to be 1000 steps/mm based on a rough measurement around the screw revolutions and extrusion length over one minute. Although this seemed to work fine when manually extruding a bead of material, it was observed during printing that the extrusion rate was completely different, therefore, an increase from 1000 to 1300 steps/mm was introduced to see what impact it would make. The expected length of extrudate was 100mm whereas the result was 80mm. This was incorrect, so an attempt was made using the previously mentioned equation (5.1), the result came to around 1600 steps/mm. The results had improved, but not significantly.

Further testing during printing revealed a much more consistent bead and formed proper bonds between layers. More testing was carried out to see if increasing the steps per millimeter would produce better results; this only destabilised the drive motor causing skipping. The maximum calibrated print speed came out at 10 mm/s with the drive screw at 7.3 rpm before the drive motor started to experience skipping. It was soon discovered that there is an extrusion multiplier feature inside the Slic3r software that alters the extrusion output during printing by a set value. The recommended range is between 0 and 1 which represent 0 to 100% extrusion output multiplier. After running some trial-and-error tests, the results for some different materials are shown in Table 5.1.

The table shows how much the extrusion multiplier value was out by and the differences between the materials. A good example is the PLA flax fiber mix, compared to the normal PLA with

Table 5.2: These are some of the common printer settings accessed in Slic3r and used to manipulate the printing characteristics

Common printer settings	Meaning
Layer Height	The height is the thickness of each layer and can affect the resolution of the print.
Infill	This is the fill inside the perimeter of the object. It can vary through density, pattern and angle which can affect the structure and directional strength of the printed part.
Skirt	This is a specified perimeter around the object which prolongs the time between layers helping with both cooling and,to help smooth out the extrusion.
Raft and Support	Raft generates initial support layers to help with part adhesion to the build platform. Support is typically internal but,is used to generate minimal structures to aid overhanging material.
Printer Speed	The print speed dictates how fast the axes move the extruder around (distance per second) which also directly influences,how much material is extruded over time.
Extrusion Width	This is how thick the bead or road of material will be once it has been deposited.
Overlap	This is how far the bead of material will overlap the perimeter during the printing of infill. The percentage of,overlap is related to the thickness of the deposited bead.
Filament Diameter	This is the thickness of the filament being fed into a filament extruder. This is a precise measurement and it will,change the output of material.
Extrusion Multiplier	This multiplier is a fudge factor used to adjust the output flow rate so that it correctly matches the printing speed.
Nozzle Diameter	This defines the diameter of the hole the material is extruded through.
Retraction	This feature allows the retraction of material back into the extruder in-between layer changes and before long,distance movements. This is to avoid excess material from being smeared on the part.

a 1.5mm nozzle. The introduction of flax fiber makes for a more viscous material which requires a higher extrusion rate to overcome. On the other hand, PET produced a lot more friction while extruding and came in a larger pellet size which requires a much higher multiplier to counteract. Additionally, it was being extruded through a 0.8mm nozzle adding further resistance when compared to PLA with the same nozzle size it reveals how different materials behave. Conveniently, the change in printing speed does not affect the extrusion flow rate as seen with PLA and the 0.8mm nozzle; the multiplier scales correctly with the increase.

Table 5.2 outlines the significant settings used to narrow down the printer's behaviour and produce consistent reliable results. From these options there are a few that have a heavy impact on the output parameters and were often used to find an optimal balance when changing between polymers. This is primarily done using the extrusion multiplier, but other key factors are the extrusion width, layer height, printer speed and the extrusion temperature. These are defined through testing of the material through extrusion, printing, and trial and error. Other factors such as the

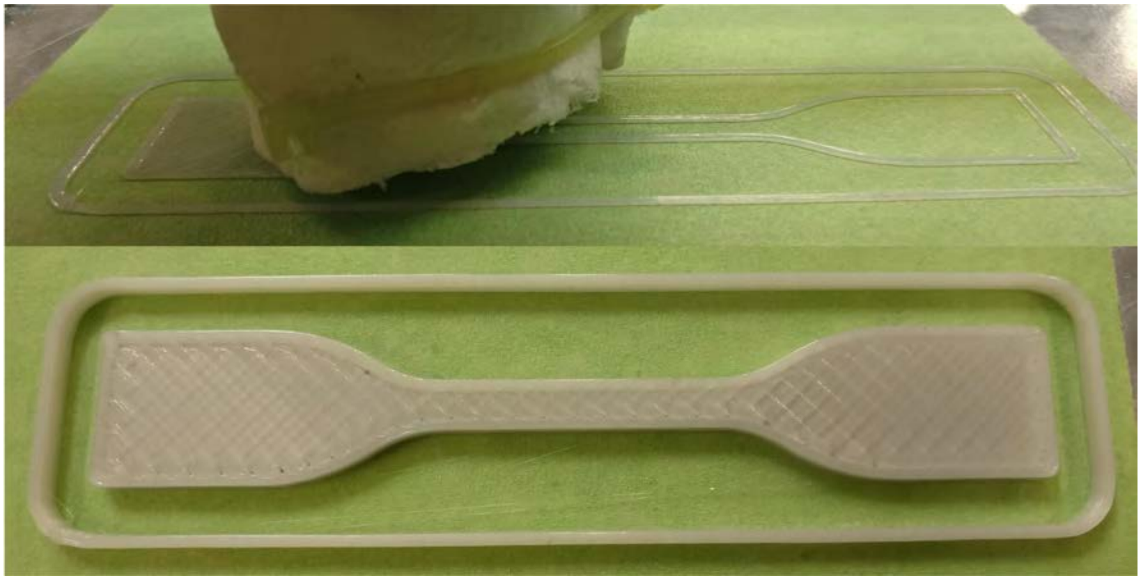


Figure 5-3: (Top) Single layer test print for settings, (Bottom) Full print with adjusted parameters and skirt

printing speed, overlap and infill are not as critical and can be adjusted as desired (within reason). The skirt printed around the parts is optional but does serve an important role in layer cooling and equalising the extrusion flow. The setting that is not altered is the filament diameter, as this could potentially offset the scalability and more importantly the relationship between the drive motors steps per revolution and the output quantity.

When inputting a new polymer into the extruder, the melt temperature for continuous extrusion needs to be found. This is done by finding the materials normal melt range and conducting a trial extrusion, adjusting the temperature while extruding to find the optimal value. For PLA the temperature range is between 170 to 180°C, while PET is between 215 and 225°C. From here a trial extrusion is performed to determine the correct printing parameters. Instead of using the drip feeder, material is controlled by hand feeding small amounts into the hopper while the print starts (Fig. 5-3).

When testing the extrusion, if the extruded path is broken, inconsistent or amplified, the extrusion multiplier is adjusted to compensate for the error and the test is repeated to pinpoint the ideal value. Once consistency is achieved, measurements are made of the path width and height for further adjustments to the printing parameters. The width should be close to the nozzle size, if it is too thin the temperature could be too high and if it is too wide there may be a moisture problem. Every material is different in terms of the extrusion conditions, from melt temperature, to viscosity, swelling and adhesion to the printing bed. The print is then progressed to make sure the parameters are maintained through an entire print; otherwise small adjustments can be made.

Figure 5-4: Continued testing from the early fiber blend to just PLA

Figure 5-5: 1.5mm aerated PLA extrudate

Following the changeover from the original DC motor to a stepper motor, came the improvements to the extruder cooling design as discussed in Section 4.2.2. These changes also solved many of heating and transport issues which directly impacted the extruder's performance. The other major improvement that helped the process were the addition of a drip or starve feeding hopper, this controls the feed of material into the system as described in Section 4.2.1. These two changes helped to improve the consistency of the system by focussing the melt zone of the extruder, and by conveying the necessary material quantities. Possibly the biggest change made to preserving the consistency during printing is to reduce the moisture content within the material itself. This alone helps prevent the effects of excess heating, material sticking together, air entrapment and output fluctuations. As testing using PLA was making progress (Fig. 5-4), prior to refining the software printing parameters, process problems needed identifying and improvements to the system made.

When the process is not quite right there are a few obvious changes in the output, these are

Figure 5-6: (Left) High moisture content, (Middle) Insufficient material feed, (Right) Overheated material

Figure 5-7: Test printed 40% infill part with collapsed bridging on top layer

outlined on the following figures. Fig. 5-5 shows a collapsed air bubble in the extruded bead. This is a prime example of why material has to be dried prior to entering the extruder.

Fig. 5-6 shows several instances of where an inconsistent flow rate occurs, but the reason behind these originate from different problems. These features are caused by an inconsistent output of material, but the root cause can be anything from moisture content, to excessive heating, to material starvation, inaccuracies in the mechanical axis and even an issue as simple as the wrong print settings. These problems cause fluctuations in the output which results in a reduced extrusion width, thus leaving a gap between the paths.

Fig. 5-7 shows a sample being tested with a fill density of 40% and on the final layer the extrusion started sagging over the fill gaps. This is affected by a setting called the bridge flow ratio.

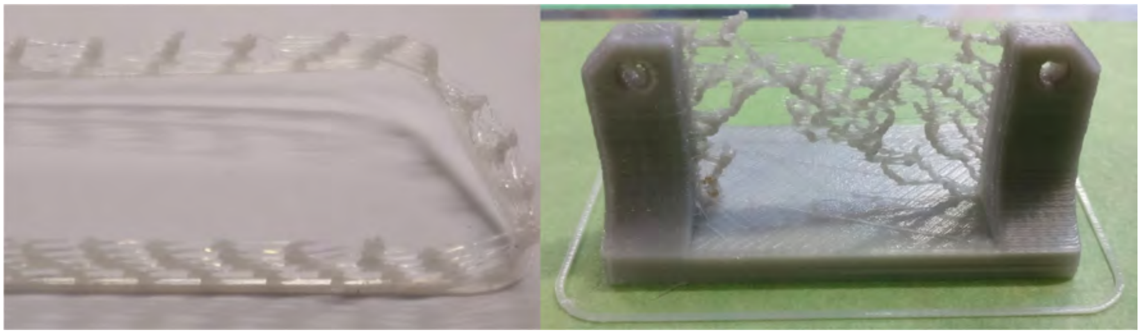


Figure 5-8: (Left) Stuttering drive motor caused oozing around the perimeter, (Right) Oozing between movements across the part

The ratio is set at 1 by default, but lowering it helps to pull the extrusion to prevent sagging by overlapping the material paths. The optimal setting was found to be about 0.14.

Fig. 5-8 shows the effect of material oozing from the nozzle during a change of layer or a long-distance move between paths. This can be prevented in filament printers by withdrawing the material before a layer change or long moves. The act of withdrawing material in a pellet extruder does not have an immediate effect as there is a certain amount of pressure and flow to counteract. Another option is to have a wipe function between layer changes to scrape off any oozing from the tip. A third option is to print a skirt as an added perimeter around the part (Fig. 5-3), by doing so it clears the nozzle and equalises the extruder after a lot of stop/start manoeuvres.

One visual issue with oozing that occurs between layers, is when the nozzle moves across the part to begin the following layer, the oozed material creates a streak across the surface. The addition of a skirt, however, does not prevent the extruder from crossing over the printed part on its way to the beginning of the perimeter. There is however an option to avoid perimeters, but this only applies to a path that ends along a perimeter. If the path ends inside a perimeter (completes infill), the travel path has to cut through it anyway and can cause the printer to act erratically.

Where this problem exists during the printing process, it also occurs at the beginning of the print. When the start button is pressed, the printer has to go through a routine to initialise all axes and guide the extruder down towards the surface. The time it takes to do this takes upwards of half a minute, which is time for heat to build in the molten polymer. This results in a change in viscosity causing oozing to start which drags across the print bed and can affect the beginning of the print.

A few lines of code were added to the start g-code script to act as a purge and wipe function (Fig. 5-9). The script starts after the initialisation of the axis, it resets the position of the extruder and moves the extruder to the back-left corner of the build plate 40mm above. The extruder then

```
G92 E0                                ; set position of extruder to
G1 X0.000 Y178.000 Z40.000 F600.000   ; move to position (X,Y,Z,feedrate)
G1 E150                               ; move position of extruder to 150
G1 Z3.100                             ; now get close
G1 X50.000 Y178.000 F2400.000         ; remove excess on platform
```

Figure 5-9: This is a set of g-code instructions written to extrude and wipe the nozzle before the print begins

Figure 5-10: (Left) Excessive heat build-up caused runny viscosity, (Right) Insufficient layer cooling as the layer size reduced

outputs 150mm of extrusion to clear out any problematic material, then moves very close to the build plate and draws a straight line 50mm long to clear the nozzle before beginning the print code.

Fig. 5-10 shows the effect of heat on the viscosity of the extruded polymer. The left most image is what happens when insufficient cooling is applied to the extruder. When the material was not being extruded, a pool of molten polymer was created as the viscosity acted more like a liquid and drizzled out of the tip. The right image shows what happens when there is insufficient cooling between layers of the printed part. This illustrates why cooling and time between layers is a necessary feature. The pyramid was printed at 40% infill, without a skirt around it (Fig. 5-10), meaning there is much less time between layers. Additionally, the bed is heated, ultimately causing the top of the pyramid to lose its shape and form a molten blob. After this test an additional fan was added to the printer and directed at the part to create sufficient layer cooling as an attempt to avoid this problem.

Fig. 5-11 shows the result of using an aluminium extruder, and the amount of wear that happens inside the extruder. When the new extruder barrel was created there was about 0.02 and 0.03mm of clearance between the edge of the screw and the wall of the barrel. Although the clearance

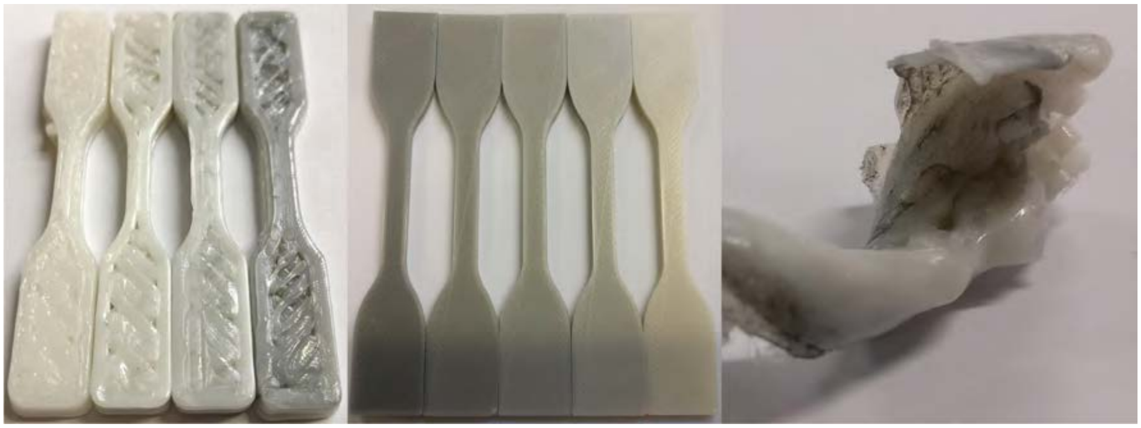


Figure 5-11: (Left) - (Middle) Visible build-up and mixing of aluminium contamination, (Right) Unmixed aluminium powder caused through rubbing

between the screw and the barrel was around what is seen in standard designs, this extruder is not, by any means, standard. Since the screw is made of hardened tool steel, during extrusion either the screw or the material friction generates enough rubbing on the barrel wall to cause an erosive effect. This erosion creates very fine aluminium particles to shave off and contaminate the molten material. The furthest image on the right shows the aluminium powder that has rubbed off but has not yet mixed with the PLA. In the left and middle images, it shows the contamination levels, as the barrel wore away and reached an equilibrium, the contamination visually reduced to return back to a normal level. As this extruder design is used more, the barrel will eventually start to affect the extruder’s performance, and with the use of composite material the rate of erosion could be accelerated. A move to a more suitable material for the melt zone such as steel could, therefore, be a suitable solution.

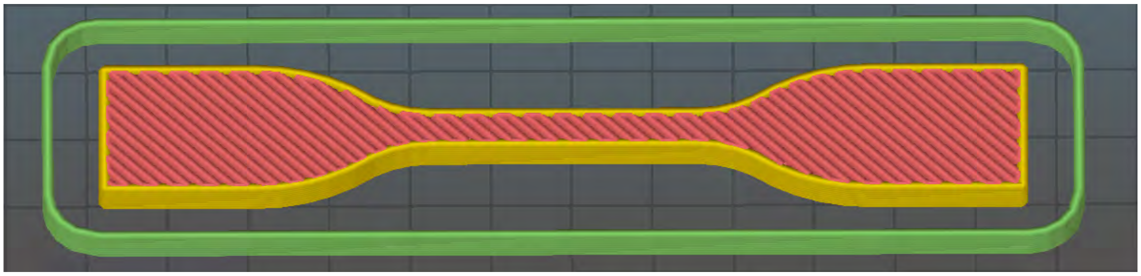


Figure 5-12: Visual representation of the slicing operation carried out in Slic3r

5.2 Part Preparation

The process of preparing for extrusion starts off with preparing the material for printing. The size of the material entering the extruder whether it is in pellet form or some type of recycled chunks, should be somewhere between 1 and 3mm cubed (Section 3.2 (Fig. 3-2)), but can be slightly larger. If the material is too fine, the particles will heat up rapidly on the way down the barrel and group together, creating unwanted blockages.

Once a suitable material is chosen, and before printing/calibration should begin, the material needs to be sufficiently dried out. If it is not dried, this can result in many problems such as excess die swelling, potential air bubbles and fluctuations, and increased likelihood of agglomeration of the pellets during transport. For the PLA and PET testing conducted, the material was placed in a heated chamber at 72°C for a minimum of 4 hours to several days. The printing platform is placed in a conditioned room at 24°C to maintain a stable environment; this not only helps with the cooling side of things, but also provides consistency by preventing delamination from occurring on the heated print bed. Before beginning a print, calibration of the printer needs to be carried out in accordance with the chosen material (as discussed in the previous section) and the nozzle size being used. This involves setting the critical parameters such as the correct melt temperature, the extrusion multiplier, the extrusion width and the layer height.

Before the printing process begins, the desired object needs to be sliced with the defined parameters set in Slic3r as seen in Fig. 5-12. The infill in this instance is set to the rectilinear pattern, a solid fill density is used on all layers and the fill angle is set at the default 45°. Though this is more of a personal preference and is not a critical feature unless mechanical strength in a certain direction is desired. It is also a very good idea to put a skirt (perimeter) around the part, especially for the initial layers. As previously mentioned it can help with layer cooling, reduce the effect of oozing and to help refresh the material flow after repetitive stop/start actions.

The process of printing starts by connecting the interface (Pronterface) to the printer's control

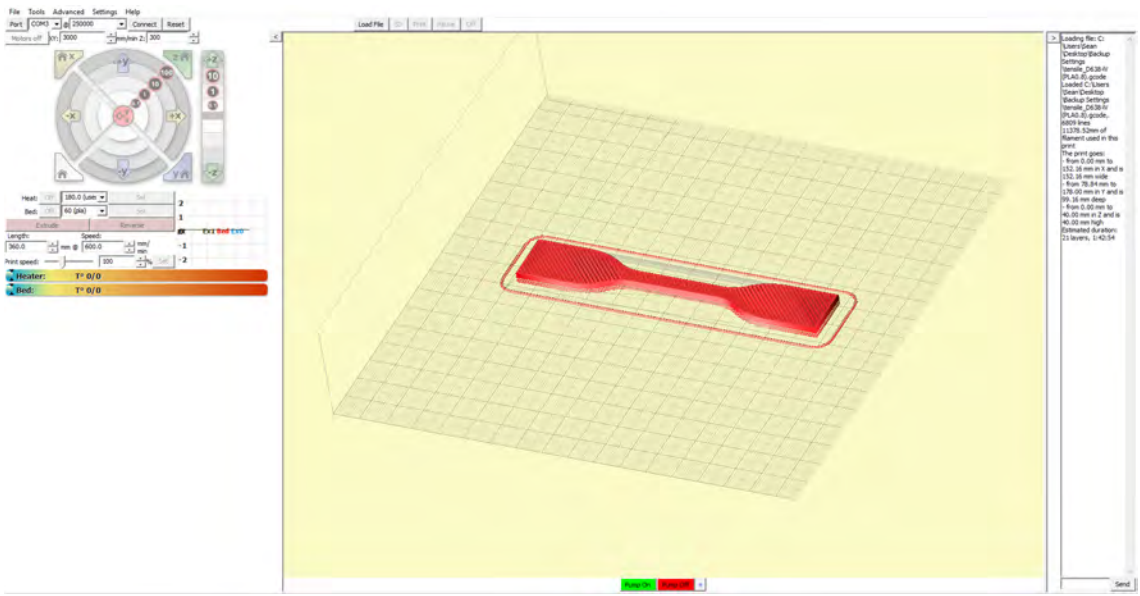


Figure 5-13: Pronterface as the graphical interface for the printer

board to monitor and control the platform. Next the heating systems are turned on to both heat up the material in the extruder and heat up the build platform for proper adhesion. The heating of the build platform is important over the course of the print to counteract the cooling and shrinking of the initial layers. As the part grows taller with each layer, the shrinking causes tension to build in the part eventually overcoming the grip on the printer bed and raising the edges of the part. By heating the bed just enough to keep the material in a soft state, it reduces the stresses building early in the process and better adheres the material to the platform's surface preventing delamination. For PLA, 50°C is just on the glass transition temperature and for PET 70°C is a suitable holding temperature.

The temperature is controlled separately by a PID controller, so the printer controller has no power over a thermal runaway event. Once the extruder heater is up to temperature, the coolant pump is activated to prevent the heat from rising up into the hopper and causing a block. The drive motor of the extruder is then turned on and fresh material is run through for a few minutes prior to printing. This is to equalise the system and allow the output to reach a uniform consistency. The most recent extruder design does not currently have an inner barrel temperature sensor to know when the extruder has reached optimal printing conditions. If the melt zone is not fully developed, it will impact the output flow rate during printing.

Once a smooth consistency is being output by the extruder, the drip-feeding hopper can be mounted and filled. The drip feeder's timing for dropping material into the extruder is approximated before running a mock print as discussed in Section 4.2.1. The sliced part is then loaded into

Pronterface and the start button is pressed to begin sending the instructions (Fig. 5-13). As the part begins to print the feeder is manually turned on to moderate the material feed. If the print needs extra layer cooling the secondary fan is turned on, but this is not recommended if the extruder has only just been turned on as any extra cooling across the nose of the extruder may cause unintended fluctuations in the output. The layer cooling fan is typically turned on later in the printing process or when additional cooling is required.

Once the part is completed the heater and feeder are turned off and the pump is left running for a few minutes. This keeps the extruder's heat from propagating upwards unnecessarily melting the polymer before the next print. From here the part can be removed safely from the build plate. If something goes wrong and the extruder manages to get blocked or jammed, or material needs to be changed, the extruder needs to be taken apart and cleaned. The process for achieving this is much the same, the interface needs to be connected for control over the system, and the heater is turned on to heat up the polymer. Once melting temperature is reached the pump is turned on to prevent excess heat and for safety. After a few minutes, when the extruder is sufficiently heated, the extrusion screw can be removed (with a bit of force) and if needed the die head can also be unscrewed.

Table 5.3: Extruder Barrel Type; Printer Conditions, (a) Full aluminium water cooled block, (b) Aluminium PTFE thermal barrier water cooled block

Extruder Barrel Type	Nozzle Size (mm)	Print Speed (mm/s)	Screw Speed (rpm)	Input Quantity (g/min)	Temp. Setting (°C)	Barrel Coolant Type	Coolant Temp. (°C)
(a)	1.5	10	7.3 ± 2	0.8	185 ± 5	Glycol	52
(b)	1.5	10	7.3 ± 2	0.6	175 ± 5	Glycol/Water	27/25
(b)	0.8	12		0.18	175 ± 5	Glycol/Water	27/25
(b)	0.8	30		0.18	175 ± 5	Glycol/Water	27/25

5.3 Speed Versus Temperature

Through the extruder development process, the focus was on specific characteristics to improve the heating and cooling efficiency. This solved several problems regarding material transport, but what was not known was how these changes would affect the output performance and the quality of the print. Testing and characterisation was carried out at different stages of the development to better understand how the changes were affecting the output. As seen in Table 5.3, two different extruder designs were tested to determine if there are more than just visual quality differences. On the most recent extruder design, the nozzle size is changed, and the print speed is significantly increased to determine if there are any material property changes.

The first extruder design refers to the initial water-cooled design made from a solid piece of aluminium discussed in detail in Section 4.2.2. This design experienced heating problems which required a high concentration of glycol to raise the boiling temperature of the coolant, resulting in the efficiency of the extruder being quite poor and requiring a higher operating temperature. The second extruder design refers to the most up-to-date version with Teflon block inserted as a barrier between the watercooler and the heating zone. This is a much more efficient design, which generated a lower heat loss meaning a lower amount of heat was needed.

5.4 Nozzle Sizes

In much larger industrial applications, the die can be a very critical part of an extruder as it can be very complex, involving multiple stages, pressures and endless profile possibilities. The job of the die is to generate an even output velocity and to shape the material. Optimised conditions apply more to die geometries that are non-circular as they are more susceptible to fluctuations or changes in parameters such as temperature and flow rate. In the case of 3D printing, it is a common standard to use a circular opening for extrusion as most systems accept filament as the feedstock.

There are some key features to consider when looking at the design of an extruder's die head and the lead up to it as seen in Fig. 5-14. One of the more important features is to avoid sharp changes in the profile or geometry of any part that may affect the flow of material. If there are any sharp angles as seen in the original extruder model Section 4.2.3 (Fig. 4-20), the flow can create dead spots which can lead to fluctuations and abnormalities in the output. Other important features are the angle leading to the land (the straight long profile before the opening), and the length of the land leading to the exit hole. The land provides a sort of memory to the molten material as to retain its shape upon exiting the extrusion nozzle. By increasing the length of the land, it can improve material swelling when extruded, but there needs to be a balance, because doing so also adds more resistance which results in a large extrusion pressure. The angle leading to the land can be related to causing melt fracture where shear stresses get too high and the output forms a rough or scale like texture. The common angle range is between 30° and 40° for a fixed or self-centering screw [57], therefore a general purpose drill was used to create the profile angle which fits perfectly within range.

The extruder's die is also responsible for generating the pressure inside the extruder. The smaller the nozzle size or the more resistance it creates, the more pressure the screw needs to apply to push out the material. In the original extruder design a very uncommon imperial extrusion nozzle was used with what was meant to be a 1.2mm extrusion nozzle, but looked more like a 2mm opening and produced a bead diameter of between 1.95 to 2.3mm. Along with the development changes to the extruder also came the change to the cone angle leading to the die as well as a standardised extrusion tip used in filament extruders. This allows an easy exchange between a wide range of extrusion sizes, from 2mm down to 0.1mm nozzles.

The initial system calibration and testing was carried out using a 1.5mm diameter extrusion nozzle and the printing output achieved a consistent 1.4mm diameter extrusion at a 0.4mm layer height with a 10mm per second print speed. The nozzle diameter was then reduced to a 0.8mm diameter nozzle and the print speed was kept the same at 10mm per second. After calibration,

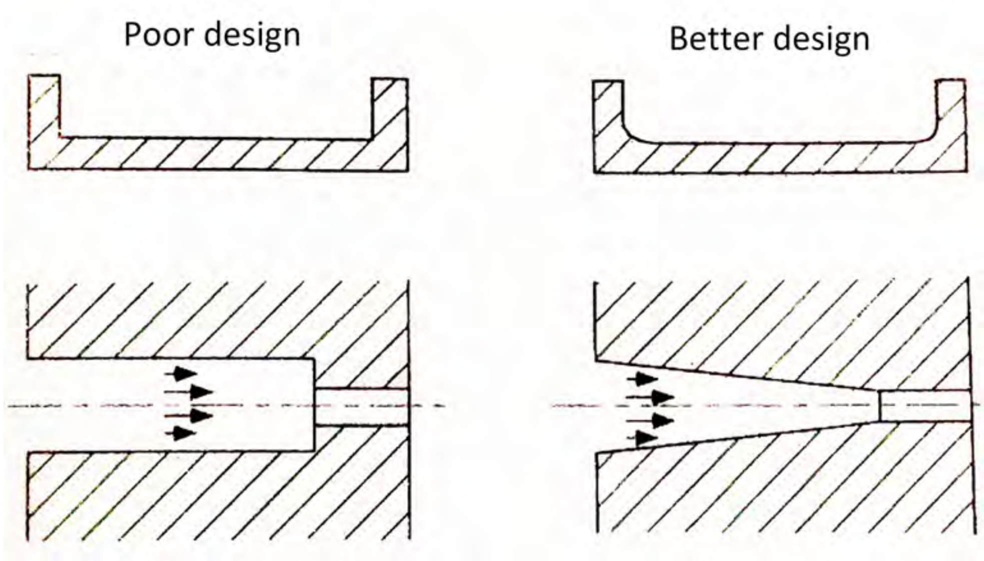


Figure 5-14: Basic considerations of die design [57]

Figure 5-15: The different sizes and types of extrusion tips used (2.0, 1.5, 1.2, 1.0, 0.8, 0.6mm)

the observed output was a consistent 0.7mm diameter extrusion at 0.2mm layer height. With an extruder that is compatible with common nozzle size, there comes a range of options to choose from as seen in Fig. 5-15.

Chapter 6

Results

The goal of this research project is to design, build and develop a biopolymer 3D printer capable of printing pelletised materials and possess the ability to experiment with composites. The printing results show the progress made at each stage of development and how this shaped the overall success of the project.

The testing and characterisation was carried out using two different extruder designs, this helped to determine if there were any print quality differences and to compare the mechanical characteristics of the printed parts to other filament-based designs. Along with comparisons made between extruder designs, observations are also made as to the impact of different nozzle sizes on the material properties, as well as a variation in the speed at which the part is produced.

6.1 Printing Results

Throughout each of the printer's development stages, the goal was to be able to successfully print biopolymer materials, with a focus on refining the extruder's functionality. Once the main platform was built and calibrated the focus was set on shaping the extruder's behaviour. Pellet extrusion types fit into two categories, continuous and discontinuous. The goal of the extruder's design was to simplify the process and create the same behaviour characteristics that more common filament printers possess. The functionality of the initial air-cooled design, was very inefficient, with heating and feeding problems. Aside from the issues, this extruder was successful in printing composite flax fiber material, but although the results became quite promising as parameters were better adapted (Fig. 6-1), the extruder's design was, by no means refined.

Figure 6-1: Air-cooled extruder progress from the first print through to a more optimised result

The air-cooled extruder was reworked to produce a water-cooled design for a more aggressive approach to cooling. The result was far greater consistency as seen in Fig. 6-2. Unfortunately, the design was still extremely problematic with persistent heating issues. This extruder proved its effectiveness with repeatable results, therefore efforts were put towards removing the major heating weakness. Instead of patching up the problems with small fixes such as the glycol coolant and pump control, a re-design of the extruder is a more sustainable and reliable solution.

The design that followed incorporated a Teflon thermal barrier as a means of preventing the propagation of heat upwards through the extruder walls and into the hopper. This focused the heating region and produced a much more reliable overall printer. In doing so this allowed the parameters to be dialled in much closer and with the added improvement of a drip feeder, the refined consistency pushed the testing into smaller nozzle sizes and faster print settings with visually comparative results seen in Fig. 6-3.

The new extruder was a success; the Teflon thermal block is so resistive that the coolant block remains at room temperature throughout printing. The printer was performing very reliably, so further testing was carried out to see if this extruder is comparable to the functionality of a filament extruder and to see if there are any limitations. As seen in Fig. 6-4(a), a test was carried out to see if a large-scale object would draw out any long-term problems and to add to the challenge, it was printed with a 40% infill; part way through the print, a magnet was inserted to act as a mount

Figure 6-2: (Top) Glycol-cooled extruder trialling parameters, (Bottom) More refined print settings

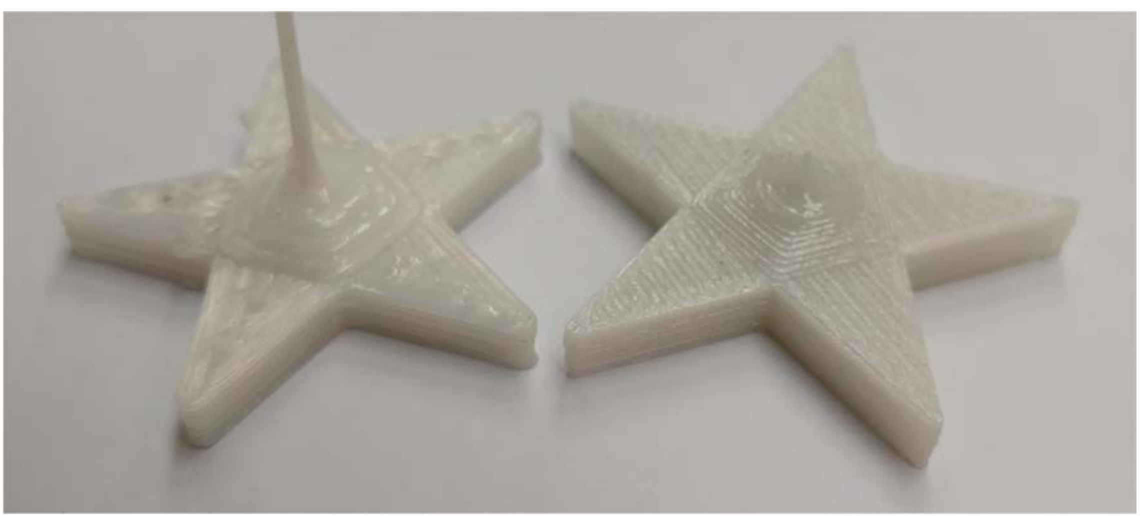


Figure 6-3: Comparison of print quality (Left) First water-cooled extruder, (Right) Refined Teflon water-cooled design

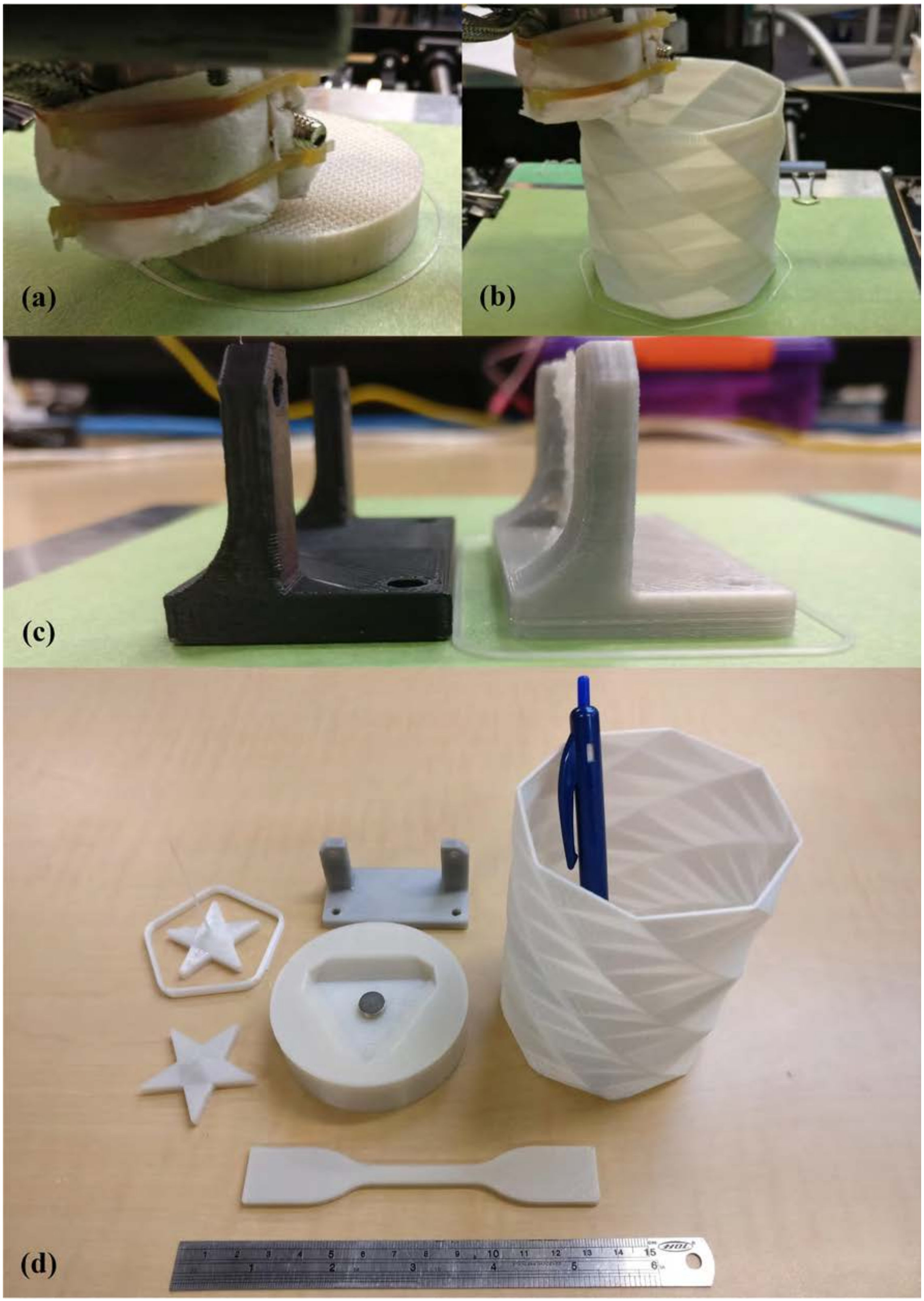


Figure 6-4: (a) Printed a large trophie mount with an internal magnet and 40% infill, (b) Tall thin-wall pencil holder, (c) A printed part comparing black ABS filament and PLA pellet, (d) Assortment of finished prints

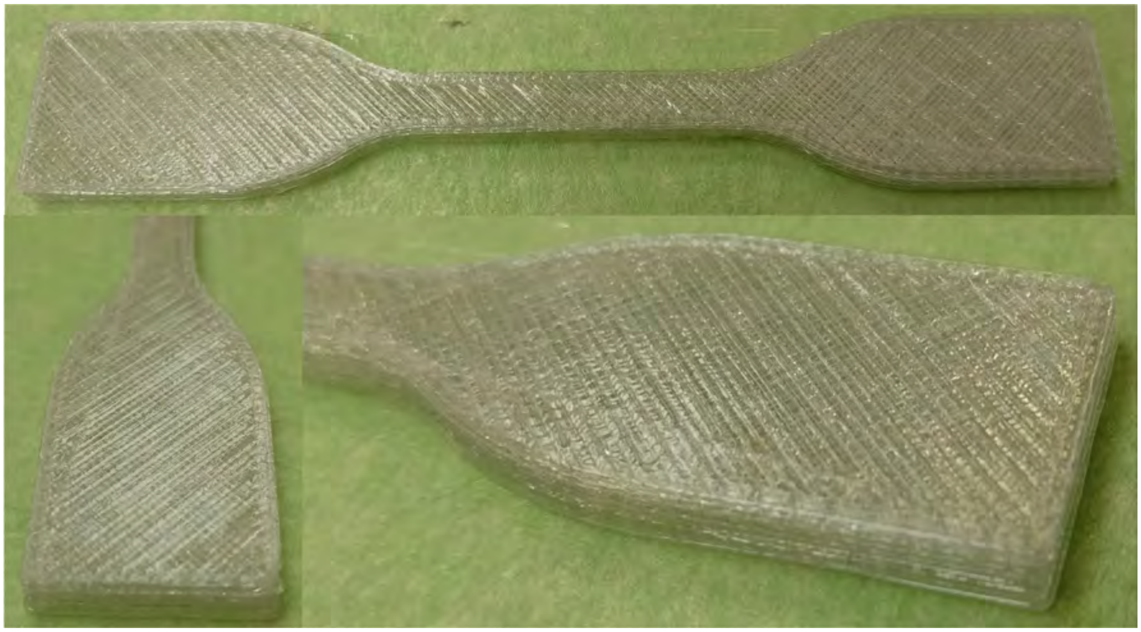


Figure 6-5: PET printed sample

for a trophy. The resulting print seen in image (d) came out far better than expected. It not only accepted a several hour-long print in one session, but there was also no loss in resolution and the large 40% infill surface bridged over perfectly, with an incredibly flat surface to the touch. Image (b) was another attempt to draw out a long print, but this time a taller, thinner, more complex object was chosen. This also printed with consistency and accuracy to completion. Image (c) shows a comparison between a black ABS part printed on an UP Plus 2 filament 3D printer, and the glycol cooled extruder, hence the slight discolouration. This object was to test its dimensional accuracy, its ability to navigate both small and large surface areas, and how it would handle heating issues. The result was quite surprising; it not only completed without melting the small surface areas, but it compares quite competitively to the professional consumer grade filament printer. The only test that did not come out successfully and needs more attention and tweaking is support material generation. The attempts that were made did successfully produce support material, but the support extruded simply did not make contact with the part that needed supporting.

Following the stress testing of the extruders design, a different biopolymer was chosen for testing. PET (Polyethylene terephthalate) has properties like glass transition and melting temperature around the same range as PLA. It was quickly found to be more of a challenge printing with PET as it does not flow as smoothly as PLA. It requires a higher melting temperature of around 220°C and has a viscosity comparable to rubber as it transitions to its molten state. This put a lot more stress on the drive motor than anticipated. After tweaking the parameters to compensate and modifying the screw to sit higher in the chamber so there is less contact with the rubber like polymer, the

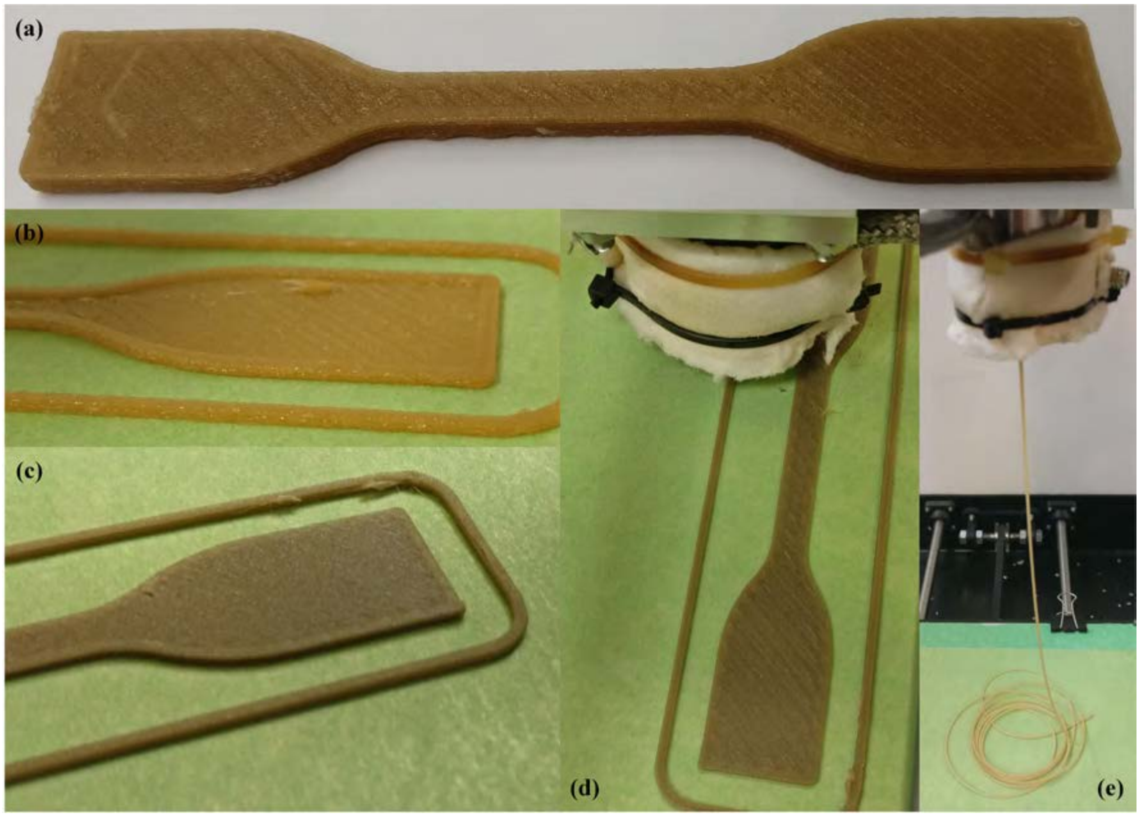


Figure 6-6: Printing samples using a Harakeke Flax Fiber and PLA composite blend; (a) Completed composite sample, (b) First attempt with new blend producing a light colour, (c) Second attempt with heating causing a dark colour, (d) Image taken during the print, (e) Extruding a bead of the composite material

results came out positive (Fig5. 6-5). The extruder was able to consistently print a bead, but when printing out samples it was more temperamental as PET likes to absorb moisture and the higher heat ended up effecting the printer over longer periods of time (more than 30 minutes). The heat was found to propagate up the screw and heat the polymer to create more friction at later stages of a print, the heat also climbed all the way up to the drive motor and gearbox. This problem is a good starting point for later design improvements; aside from this, the material was successfully printed to an acceptable standard, but it is yet to be entirely sustainable.

After trialling PET, Harakeke flax fiber PLA composite pellets were received through Scion to be tested in the new extruder. The blend is 15wt% fiber to PLA, it was found during the initial test extrusion that the composite retains a lot of moisture, therefore requiring a much longer drying period. The images seen in Fig. 6-6 are the first two prints; these were both successful. The two images on the left are the same batch of polymer, but one came out darker because it remained in the extruder longer. This is what the printer was originally designed for, and these results confirm it is a success (Fig. 6-7).

Figure 6-7: The variety of polymers tested in this extruder with a 1.5mm nozzle, (Left two) Harakeke Flax PLA composite, (Middle) PET, (Right two) PLA

Figure 6-8: Instron tensile tester demonstrating the gripped specimen and extensometer

6.2 Tensile Testing

The material tensile testing was carried out using PLA, because the extruder was initially calibrated and developed around extruding PLA as a means of later adding composites. The mechanical properties of the PLA were tested according to the ASTM D638 type IV standard. This size sample provided a middle ground between the inaccurate definition of the smaller type 'V' standard when using larger nozzles and reaching the maximum print bed size with the type 'I' standard, resulting in longer print times and more material usage. Several sample sets were printed and tensile tested in an Instron (version 5967) using a 30KN load cell. A clip-on 10mm class B-2 extensometer was used to record strain during the testing process as seen in Fig. 6-8. All sample sets used the same solid infill with the rectilinear pattern printed at a 45° angle.

Table 6.1 shows the tensile testing data gathered on each of the sample sets defined in Section

Table 6.1: (a) For parts printed without PTFE thermal barrier, liquid cooling and 1.5 mm nozzle, (b) same as (a) with PTFE thermal barrier, (c) same as (b) with 0.8 mm nozzle, and (d) same as (c) but printed at a higher speed.

	Maximum Tensile Strength (MPa)	**Average Tensile Strength (MPa)**	**Standard Deviation of Tensile Strength**	**Maximum Load (N)**	**Standard Deviation of Load**
(a)	50.7	47.8	2.65	1351.45	70.71
(b)	44.4	36.4	5.06	1088.72	124.35
(c)	51.4	48.2	1.67	1320.20	42.88
(d)	50.2	45.4	3.99	1284.84	102.26

5.3 (Table 5.3). A visual representation of the tensile data can be seen in Figures 6-9 and 6-10 the obvious anomaly is the second sample set Fig. 6-10(b). The peak and average tensile strength values are much lower than the rest, with a higher deviation/spread over the range (Fig. 6-10). The reason behind this is due to the sudden change over between the old extruder design and the new one. The tolerance between the barrel and the screw was very fine, and during the extrusion of this sample set, the screw started rubbing along the barrel wall. This caused aluminium contamination in the material as previously mentioned, but it also produced fluctuations in the output during printing. As more printing and tests were carried out, the barrel wore into a more comfortable tolerance and with the addition of a smaller diameter nozzle, the best all-around results were achieved. Sample set Fig. 6-10(d) not only achieved the highest tensile strength, but the standard deviation was by far the lowest creating a precise sample set. The final batch was printed at a higher print speed, meaning the PLA passed through the extrusion process much faster.

The resulting values came out slightly lower than the slower print; with such a small sample set and the short period of time these were made in, the reason is not clear. It could be because the polymer was heated for a shorter period of time, it could also be because of the platforms speed which could have caused inconsistencies in the print, but it could also be due to the wearing of the bore again. When looking back and comparing the new extruder's results with that of the original water-cooled design, there is no conclusive separation between the mechanical characteristics shown. However, there is clear separation between the operational efficiency as outlined in the development.

When compared to similar PLA samples tested through filament extrusion, these results look very promising with the maximum tensile values landing in the same region as most of the filament results [64].

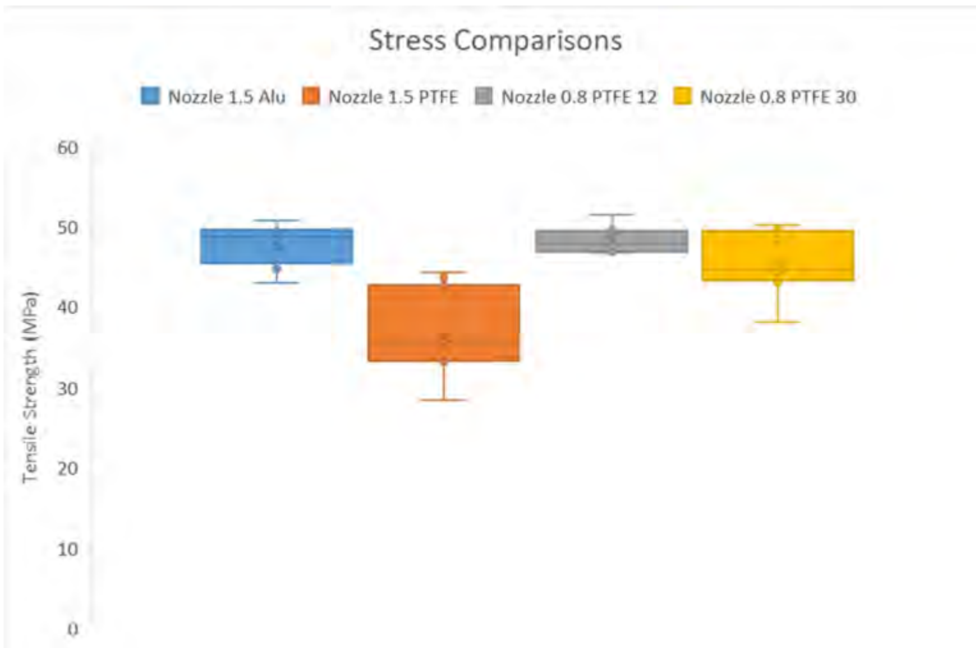


Figure 6-9: Box and whisker graph comparatively showing the tensile strength of each sample set

6.3 Recycling

Material recycling is slowly making its way into the consumer market as filament printers continue to grow in popularity. Scrap material is shredded up and fed into a separate extruder which then extrudes out new filament. The same method could also be used for this pellet extruder design, but instead of buying a separate extruder, shredded material could be put directly back into the extruder to cycle around again. A second method of recycling material is to use the designed pellet printer as a means of creating filament. This was tested successfully by extruding out filament approximately 1.75mm in diameter and extruding the filament pieces using an old Stratasys FDM Vantage 3D printer.

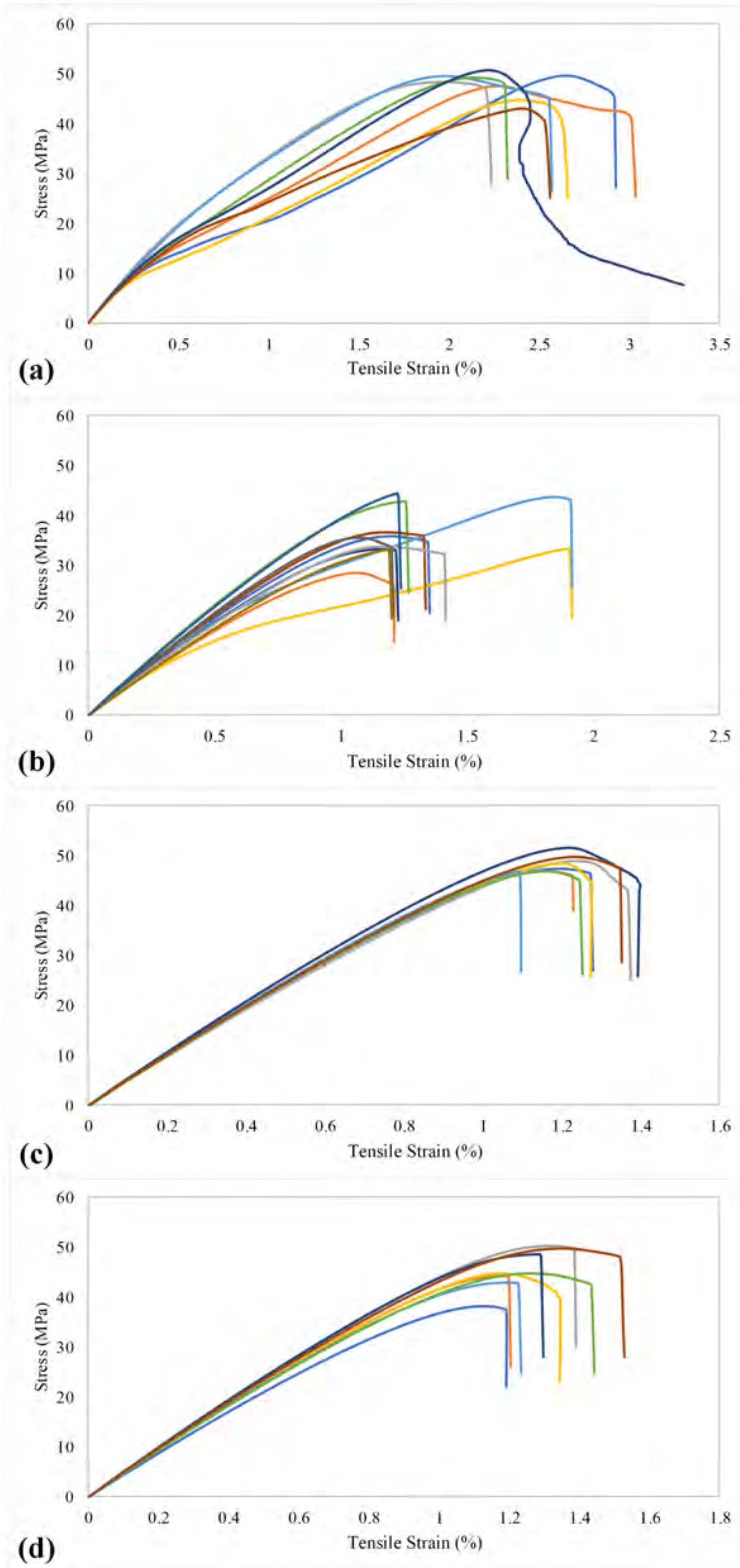


Figure 6-10: Tensile test results for four sample groups as per Table 6.1

6.4 SEM Analysis

It is well-known that the mechanical strength in FDM depends on the bonding of the extruded filament (or roads) [37, 61]. The bonding of the filament, particularly on the outer surfaces, also determines the surface quality and geometrical exactness of the printed parts with the CAD data. Therefore, to ascertain the bonding of the roads, topographical imaging of the printed parts was performed using a table top SEM (Hitachi TM3030Plus). A low voltage (5kV) imaging mode was used to avoid causing charged artefacts.

The first sample set analysed using a Scanning Electron Microscope (SEM), does not provide the best comparison as this was the initial water-cooled design defined in Table 5.3(a) using a 1.5mm nozzle. The images in Fig. 6-11 show a rough visualisation of the fracture surface, the bonding between layers and the size/shape of the bead. The bonding between layers looks almost compacted compared to that seen in Fig. 6-12 produced using a filament printer. The sizes of the voids seen in Fig. 6-12(Right) are not directly comparable to the sizes seen in Fig. 6-11. This is due several factors; the first being a severe difference in extrusion size (1.5mm versus 0.35mm), the infill is printed at different angles which affect the fracture surface (alternating 45° versus alternating parallel to pulling axis), and lastly the SEM images are comparing different magnifications (500μm versus 200μm).

With fracture surface quality and magnification aside, the ratio of bead size versus the void size in Fig. 6-11(Left) is far greater than either of the images in Fig. 6-12. There is also a clear difference between the contact surface of each layer, making for what looks like a much higher density part produced using the pellet printer. Although the part density and layer bonding appear to be superior from the pellet produced parts, the filament extrusion's maximum tensile strength for white PLA came to almost 54MPa, this is higher than the pellets maximum at 50.7MPa. But this result is probably related to the previously mentioned infill angle of the pellet samples versus the filament samples, where other literature such as [19, 28, 29], show a clear difference between tensile specimens with infill at 45° and parallel to the axis of pull.

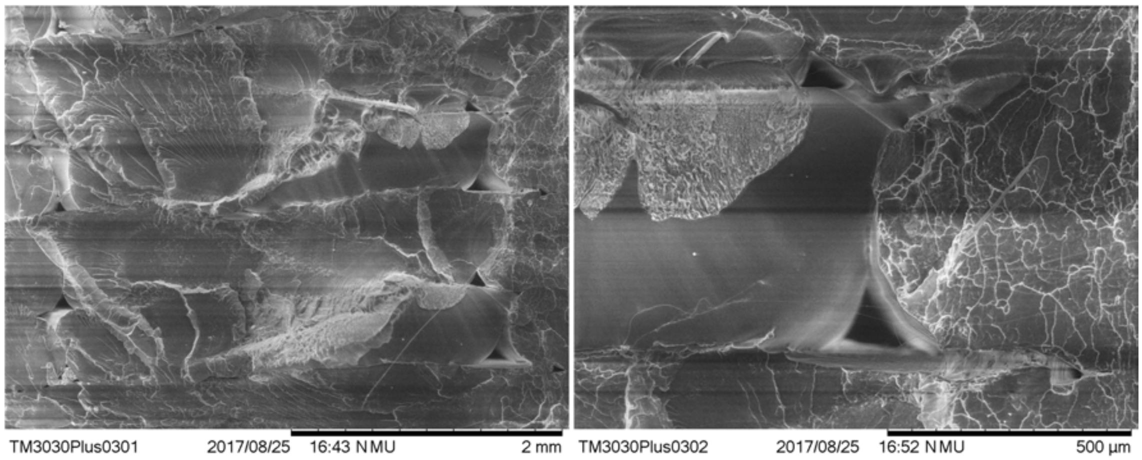


Figure 6-11: (Left) SEM result showing the layer bonding and bead shape, (Right) Close up of the voids that occur between roads

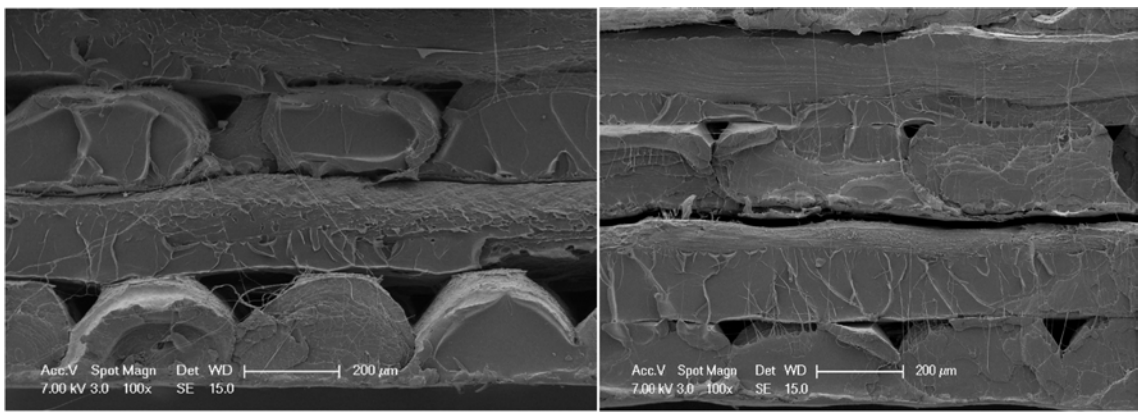


Figure 6-12: SEM results (Left) white PLA at 190°C, (Right) Natural PLA at 190°C [64]

The second sample set analysed using the SEM, was taken from the latest specimens produced using the fourth category in Table 5.3(b) with a 0.8mm nozzle. These images were taken of the specimen's top surface to visualise surface defects and roughness in comparison to samples printed on an UP Plus 2 filament 3D printer. The filament printer used PLA material with 0.2mm thickness and solid fill settings for a closer comparison. The images in both Fig. 6-13 and Fig. 6-14 show the upper and lower edge of the sample with the same magnification settings.

The pellet images alone show a very smooth surface with smooth joins between roads, however there are some very minor voids which are almost impossible to remove when so many factors are at play such as nozzle size, extrusion consistency and the actual slicing algorithms. On the other hand, looking at the filament sample, the bead shape is nowhere near as smooth/flat looking with obvious voids not only between the turning points, but also between the straight roads themselves. If this is the case throughout the whole sample, then pellet printer looks to produce a much better-

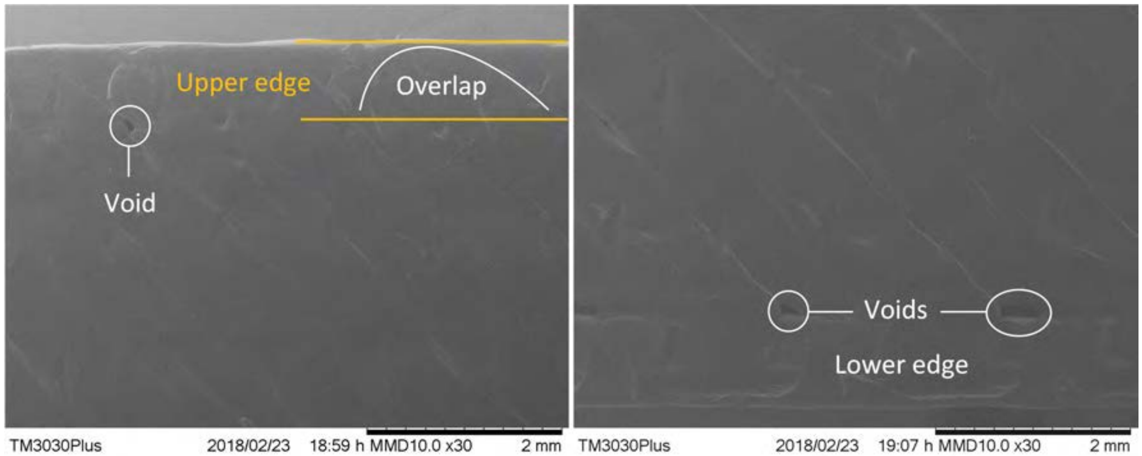


Figure 6-13: SEM surface of pellet sample (Left) Showing upper surface edge, (Right) Showing lower surface edge

quality part. The major factor in reducing the void size in the pellet sample is due to increasing the overlap around the edges, but if overdone, can result in pushing out the edges. With this said, the edge in both pellet images manage to look straighter in comparison to the filament images. An additional image for both the pellet and filament extruder was taken to show the center roads of each sample (Fig. 6-15). Both the pellet and filament sample show a straight consistent road, but the filament sample still details a ridged surface unlike the pellet sample (ignoring the tensile gripper indentations). The voids in the filament sample are also no longer present leading me to believe it generates inconsistent flow when performing a turn at the edge of the part.

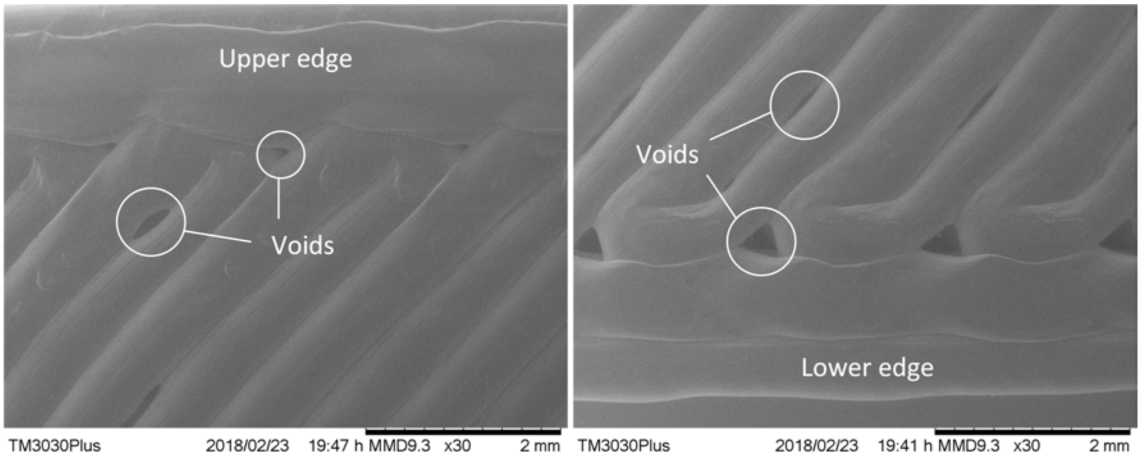


Figure 6-14: SEM surface of filament sample (Left) Showing upper surface edge, (Right) Showing lower surface edge

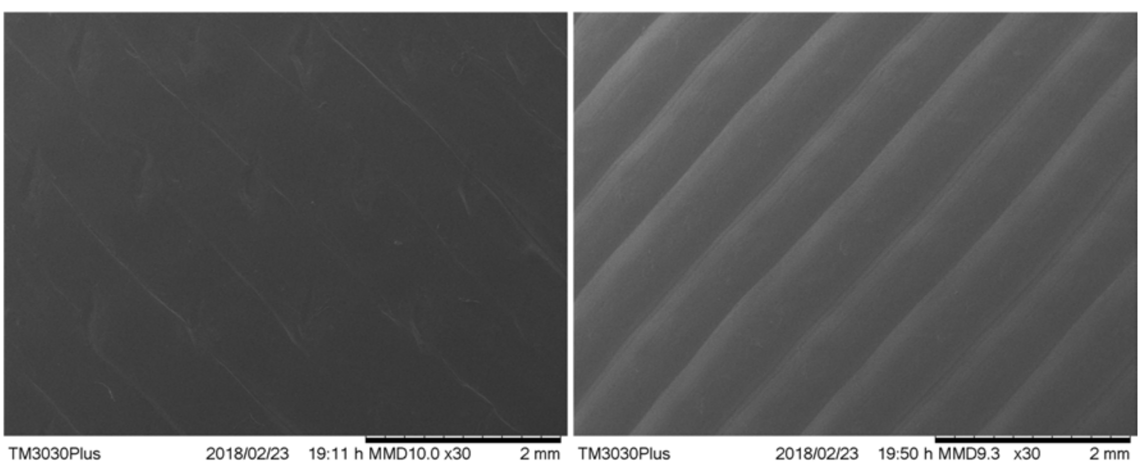


Figure 6-15: (Left) Showing central pellet sample surface, (Right) Showing central filament sample surface

Chapter 7

Discussion and Conclusion

The aim of this project was to develop a small-scale 3D printing system capable of processing biopolymer pellets with the intention of extruding composite materials. The results given in Section 6 provide viable proof of the extruder's design potential by showing that it is capable of printing functional biopolymer and composite materials at comparable quality to current marketplace systems.

The process of designing this system had to meet certain requirements for this type of extruder to not only extrude, but to behave like a 3D printer. The platform design was expected to achieve a degree of accuracy suitable for 3D printing. Its structure needed to be stable enough to support the movement of a larger than normal extruder, yet not so restrictive that any potential configuration changes would not fit. The results show the platform is more than capable of undertaking parts with a large build volume that require long print times and still maintain dimensional accuracy.

In an ideal situation, the extruder needs to act like an extruder but at the same time perform like a 3D printer. A functional 3D printing extruder was achieved by simplifying the extrusion process; this involved reducing the requirements of the screw and focusing the heating process to a single melt zone. In order for such a small design to localise the heated area, a liquid cooling system was implemented. This successfully reduced the operating temperatures and improved the extrusion consistency which was confirmed using a thermal imaging camera in Appendix A. To further improve the output consistency, the creation of a drip feeder was added to control the feed of polymer into the system. The results show the effectiveness of this addition with success in processing several types of material, as well as providing the flexibility to change nozzle size and processing speeds. Although this extruder met the intended goals, it is not a perfect solution as there are several separate processes that make up the system. This configuration works if everything does its job, but this can cause problems later if something performs incorrectly.

The tensile results support the development process of the extruder by showing how the improvements have produced consistency/repeatability in the material's mechanical properties. Not only did this printer design achieve the objective of printing biopolymer pellets, the results obtained are comparable to current filament printers available on the market. Even with the current applied controls and basic design, the behaviour of the pellet extruder can mimic filament functionality to produce dimensionally accurate parts. Beyond this, the extruder has access to a much broader spectrum of materials and combinations, thus opening the door to many experimental possibilities.

In conclusion an extrusion system has been successfully developed that allows the 3D printing of pellets with similar consistency and strength as found in the commercially available printers of the same class. This innovative extruder design is a compact unit that has the potential to be mounted on a supportive open-source scanning system and used for printing just like the filament-based counterparts. Through testing and characterization, it has been confirmed that the printed parts attain strength similar to the values reported in the literature. Furthermore, the aesthetic quality and inner layer bonding of the extrusion are equal or better in some cases than its counterparts due to uniform mixing and heating of the extruded material.

During testing a number of problems were found and some were rectified through design changes or optimization of the parameters. However, the presented system is in no way devoid of problems and limitations. Section 5.1 shows various issues including the clogging of the screw with the print material, improper filling, inconsistent bonding, and colour change of the printed material as the result of contamination through extruder design. This is a work in progress and opportunities for further improvements and enhancements are abundant. For example, the addition of more sensors to monitor the internal pressure, heating and cooling effects on the system can help with better control over the heat flow.

Furthermore, this project has not only been successful in development, it has also generated an accepted publication in the International Journal of Advanced Manufacturing Technology (IJAMT) and has been showcased at several conferences with a great amount of interest. Evidence of this can be seen in Appendices B and C.

Chapter 8

Future Recommendations

- The largest design limitation that needs looking into is the cooling of the screw. This is preventing the use of materials that require higher temperatures to melt as heat propagates upwards much faster and effecting the pellet flow characteristics.
- The second design modification that needs looking into is the material that the extruder barrel is made from. The cooling block being made from aluminium benefits greatly from the rapid thermal transfer, the heating zone does not necessarily need fast transfers, but does need improvements to hardness to prevent the material from rapidly wearing.
- The third design improvement would be to the feeder. It is currently quite rough in accuracy and not very consistent with a reverse function being called every revolution. Although the pellets are of a varying size and of a non-uniform shape, the consistency could definitely use refining.
- In terms of software, the methods of feedback during different stages of a print cycle could be further looked into. This could be the inclusion of a pressure transducer to help with creating consistency in the start-up procedure before printing begins. Or maybe looking at potential vision processing solutions for further system feedback during printing.
- Because there are few available pellet printing machines currently on the market, and the ones that are present are either too large or do not sit within an affordable price range. Therefore, a potential business opportunity could be explored to further develop this system into something that is production ready, or at a minimum can provided to institutes that would like to further their own research.

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Appendix A

Thermal Images

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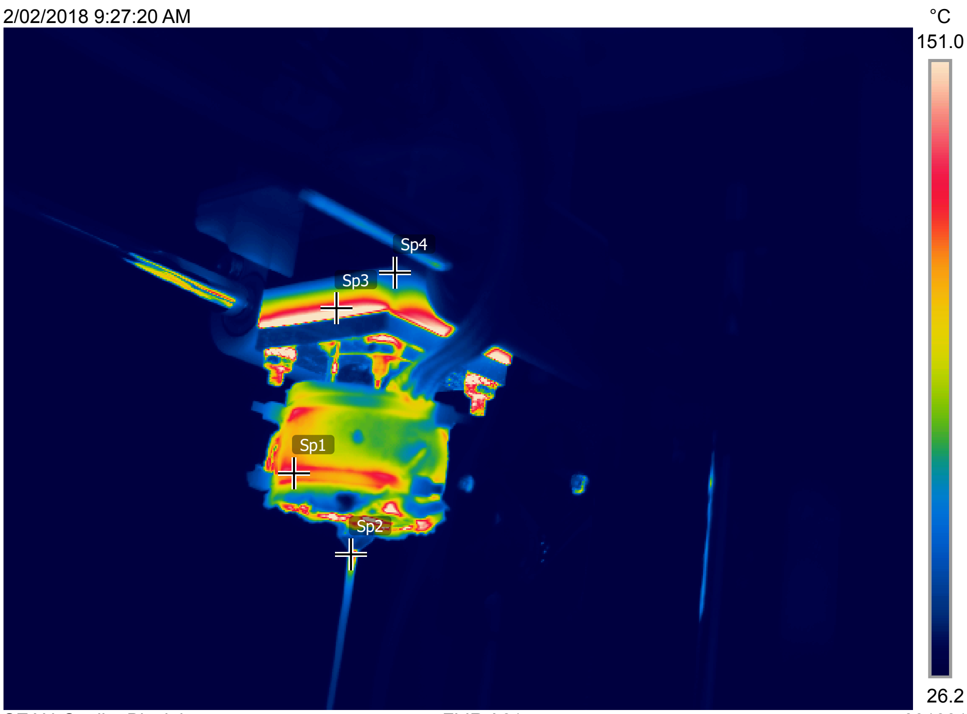

SEAN-CoolingBlock.jpg FLIR A615 55001331

Measurements

Sp1	121.0 °C
Sp2	139.4 °C
Sp3	143.0 °C
Sp4	52.7 °C

Parameters

Emissivity	0.9
Refl. temp.	20 °C

Note

Temperatures are out by 3degC

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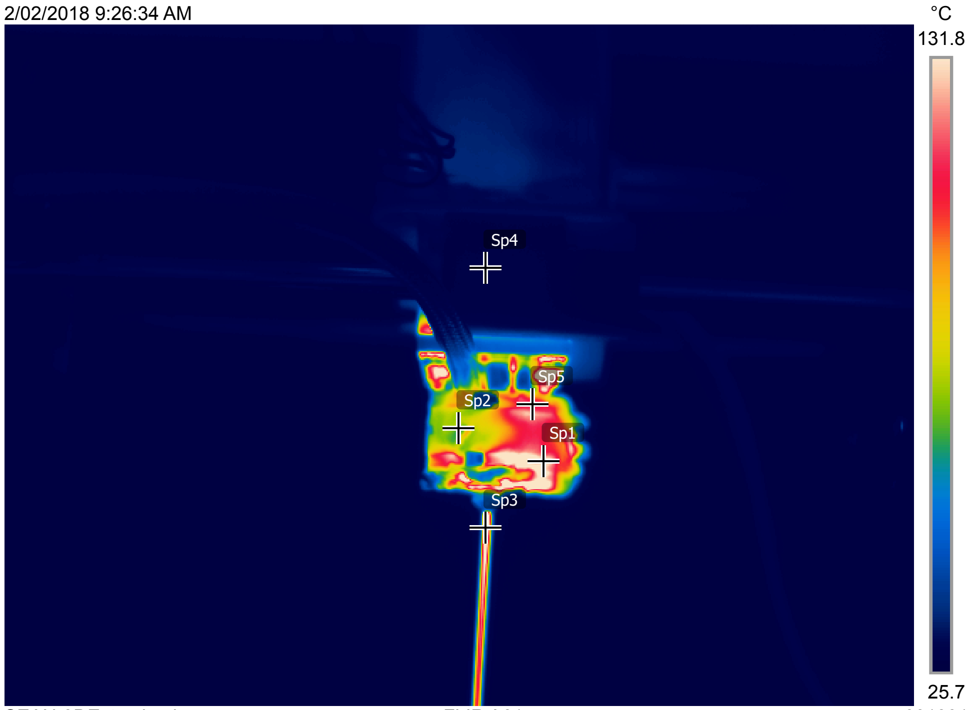

SEAN-3DExtrusion.jpg FLIR A615 55001331

Measurements

Sp1	130.8 °C
Sp2	78.1 °C
Sp3	140.4 °C
Sp4	28.2 °C
Sp5	116.8 °C

Parameters

Emissivity	0.9
Refl. temp.	20 °C

Appendix B

Publication

Int J Adv Manuf Technol manuscript No.
(will be inserted by the editor)

Design and Development of an Extrusion System for 3D Printing Biopolymer Pellets

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Received: 30/09/2017 / Accepted: date

Abstract The extrusion system is an integral part of any fused deposition style 3D printing technique. However, the extruder designs found in commercial and hobbyist printers are mostly suitable for materials in filament form. While printing with a filament is not a problem per se, the printing of materials that may not be readily available in the filament form or not commercially viable remains untapped, e.g. biopolymers, material blends, etc. This is particularly an issue in the research and hobbyist space where the capability of printing a variety of materials or materials recycled from already printed parts may be of utmost importance. This paper presents a pellet based extrusion system for the 3D printing of biopolymers. The system has been designed from first principles and therefore can be extended to other materials with parameter adjustments or slight hardware modifications. A robust mechatronic design has been realized using an unconventional yet simplistic approach. The extrusion system uses a series of control factors to generate a consistent output of material over the course of a print. The platform and surrounding processes are setup so that software can be used to define the printing parameters, this allows a simpler adaption to different materials. The utility of the extruder is demonstrated through extensive printing and testing of the printed parts.

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Keywords Pellet extrusion · Biopolymer printing · Extruder design · Fused deposition modelling · Polylactic acid

1 Introduction

Additive manufacturing (AM), or 3D printing is a rapidly growing technology which allows the production of parts with complex geometries without requiring special tooling. Over the past decade or so, advancements have driven the technology towards a far lower cost and consumer friendly direction. The use of 3D printing stretches across several areas such as industrial and consumer applications, artistry, bioprinting, automation, medical applications, and open source hobbyist printing [15, 16, 20, 27]. There are many types of AM technologies that allow rapid concept generation to proof a prototype design. Some of the most common technologies are stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and selective laser melting (SLM) [7, 16, 13, 27]. However, the most popular of these technologies is the FDM printer; these printers typically have a lower operating cost and require much lower maintenance [3].

Generally, FDM operates by using a pre-formulated thermoplastic filament and extruding it through a hot print head onto a 2D platform slowly building a 3D object layer by layer. This method of extrusion is simple, consistent and can be applied to almost any material that can be pushed out of a die and hardens quickly. The most common thermoplastic materials used are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). In recent years there has been an increase in filament types with different properties [12]. Many new

Appendix C

Conference Posters

NZProduct Accelerator

Project Title: Pellet Based Biopolymer 3D Printer

Sean Whyman, Masters Student, 2016, Affiliation: Massey University,
Supervisor(s): Dr. Khalid Arif, A/Prof. Johan Potgieter, Advisor(s): Dr. Frazer Noble

Improving upon methods of pellet extrusion through Fused Deposition Modelling using biopolymer materials

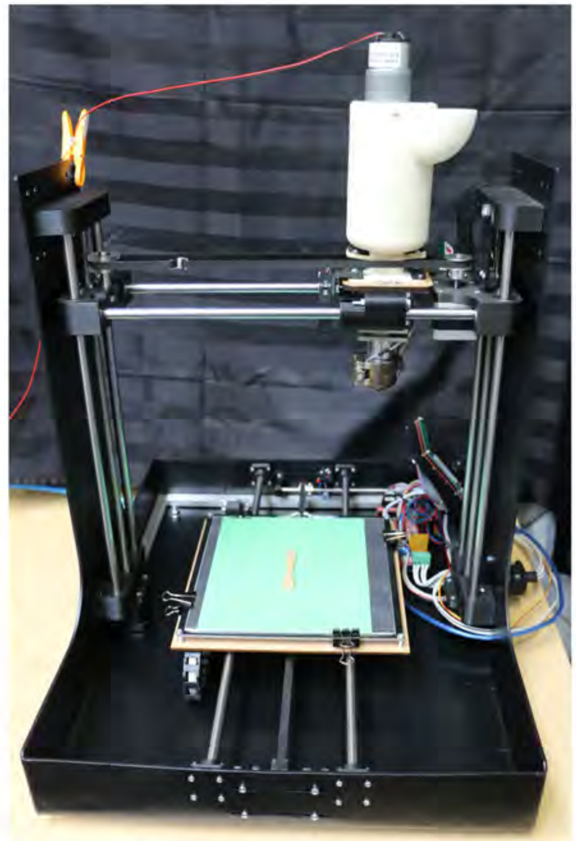
- This is a testing platform for materials, extrusion techniques and printing methods.

- The aim of this platform is to perform at the level of other 3D printers, with the added benefit of using pelletised materials.

- By using pelletised materials, it broadens the boundary around which materials and combinations can be used.

- In addition to materials testing, future goals are to incorporate these methods into other areas for the added benefits of its design.

(Figure 1) Printed test pieces for material research



(Figure 2) Full pellet 3D printer test platform setup

- The printer design is based around the previously built extruder and hopper with modification in mind.

- This setup uses open source electronics for simplicity and customisation. The software used is highly customisable and user friendly for future adjustments and fine tuning.

- The use of printed parts also allows for adjustments and future design modification.

(Figure 3) Pinting using a mixture of PLA and Harakeke flax fibers

Project Title: PET Pellet Printing

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Supervisor(s): Dr. Khalid Arif, A/Prof. Johan Potgieter

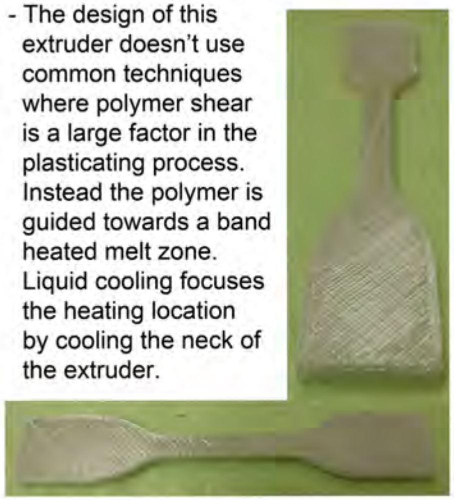
NZ Product Accelerator

Using Fused Deposition Modelling techniques to print pelletised materials

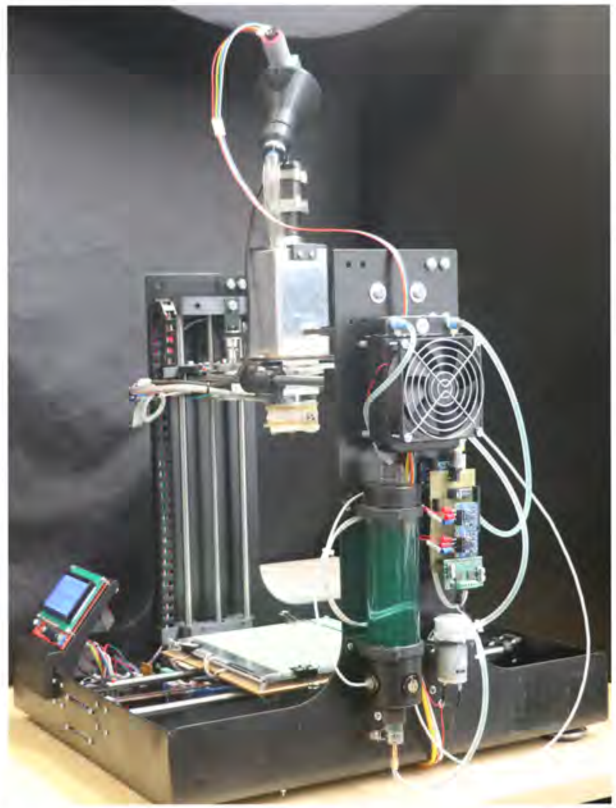
- This is a testing platform for materials, extrusion techniques and printing methods using pellet materials.

- This printer takes pellet materials and relies on gravity feeding to transport the material towards the heating zone. The screw then forces the material out throught the extrusion tip for printing.

- The design of this extruder doesn't use common techniques where polymer shear is a large factor in the plasticating process. Instead the polymer is guided towards a band heated melt zone. Liquid cooling focuses the heating location by cooling the neck of the extruder.



(Figure 1) Printed test pieces for material research

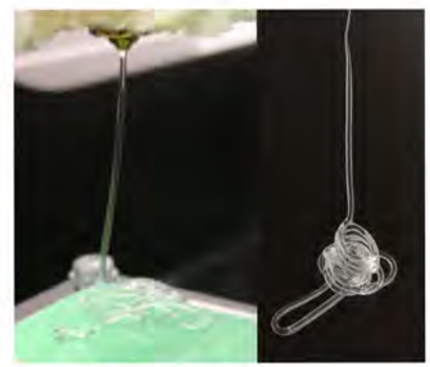


(Figure 2) Full pellet 3D printing test platform

- This printer uses a combination of liquid cooling, temperature monitoring and starve feeding to control the materials extrusion parameters.

- This printer is based on open source designs and hardware for simplicity and customisation. The software used is highly customisable and user-friendly for future adjustments and fine tuning.

- The resultant extrusion seen in Figures 1 and 3 show the PET extrusion output from this platform and process.



(Figure 3) Extrusion of PET pellets

Development of a Pellet Base Biopolymer 3D Printer

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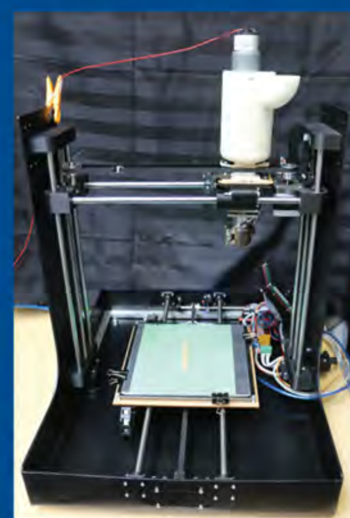
INTRODUCTION

This project is aimed at accurately and consistently 3D printing pellet based materials through a pellet extrusion system. Issues seen among common 3D printing systems using a pre-formulated filament are the lack of mixing capability and a restriction around the types of materials that are capable of extrusion. Therefore, a system has been designed and built to test and develop an extruder that can overcome these issues and explore materials such as biopolymers infused with Harakeke flax fibres. The platform supporting the extruder is based off currently available consumer Fused Deposition Modelling (FDM) printers. It uses a simple Cartesian coordinate system to deposit material around a single x/y plane and increases the z axis to create a layered or stepped 3D object.

The polymer extruder is largely based off standard single screw extruder designs, but because of the nature of this system, the extruder must also consider both filament and common screw extruder characteristics. For this to be practical, the extruder needs to be compact enough for it to be usable on a small platform, but also powerful enough as to perform like an extruder. The extruder is comprised of several parts; the screw at the heart of the extruder, the barrel and cooling system, the hopper and the die head. The development focus of the extruder is to not only extrude the intended polymer, but to do it more consistently and reliably over longer periods of time.
The extruder was designed with a short barrel and heating band to restrict the melt zone of the polymer. An auger drill bit is used with a rubber extrusion process in mind where it is acting more as a guide for the polymer with minimal shear. Alongside the heating, water cooling is applied as an effective method of preventing heat traveling up towards the hopper and adding to the extruders compact form factor.



The entire system runs on open-source software. This provides the necessary manupilation and customisation to accommodate any needed changes.