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ORIGINAL ARTICLE

Design and development of an extrusion system for 3D printing biopolymer pellets

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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 and material blends. 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 the 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 set up 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.

Keywords Pellet extrusion · Biopolymer printing · Extruder design · Fused deposition modeling · 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, 13, 16, 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 and 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 and novel materials are also used in FDM like nanocomposites [8], ceramics [19], and biopolymers [5].

A filament extruder operates by pressing a solid continuous strand (or bead) of material (generally polymers or mixes) down into an extrusion head where the polymer is rapidly heated and extruded. The polymer strand also acts like a piston, where the unheated section is used against the heated section to drive the polymer out through the die [23]. The printing operation then lays out the material and

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builds it up in layers to form a 3D part. If the extruder does not perform properly, the 3D printer will not produce geometrically or mechanically correct parts [9, 22]. For this reason, a great amount of effort has been dedicated by many researchers, in the past, to improve the extruder designs and characterize their performance [1, 2]. However, there are still some areas where further improvement is needed. One such area is the extrusion of pellets instead of filaments to print objects with specialty and mixes of materials. The process of filament formation adds at least one additional heating step to the material. For some biomaterials, this additional heating step may not be desired and thus may require the usage of raw or pelletized material extrusion [6]. This is of particular interest in the printing of biopolymers for environmental biodegradability, mechanical, or esthetic reasons. Unfortunately, pellet 3D printers exist in very few numbers and either do not suit the intended small scale or do not provide the versatility and freedom to configure and develop.

In this paper, we present the design and development of a pellet extruder which is capable of extruding mixes of biopolymers with common printable polymers like PLA, with a pellet size ranging from 1−3 mm in both diameter and length. Our system is designed from scratch considering basic extrusion theory and utilizes advanced features like liquid cooling, temperature control, and controlled feeding of pellets. The overall goal of the proposed extrusion system is to be able to print Harakeke flax fiber mixed with PLA polymer with consistency and without burning. The paper begins with the details of the proposed extrusion printer design (Section 2). Development of the extruder system is described in Section 3. Section 4 describes the optimization of processes while Section 5 gives details of the testing and characterization of the printed parts.

2 Pellet extrusion printer design

There are two fundamental components of any FDM 3D printer: the extruder assembly and the mechanical scanning system. The extruder's ability to reliably and accurately output the correct quantity of material over varying distances is fundamental to the printing process. However, the accuracy of the extruded material is insignificant if the mechanical axis is inaccurate or has a limited capability. Consequently, both the extruder and the scanning system are needed to create esthetically and geometrically correct parts.

Filament-based extrusion is well-established in the 3D printing community [23]. However, from the FDM process point of view, it is not necessary that the extruder is only filament based; an FDM printer only requires a controllable flow of material to deposit layers [25]. Therefore, other extruder designs such as a ram or syringe style printer would also belong to the FDM family [11]. This type of extrusion works by heating up material inside a barrel and forcing it out at a controlled rate using a plunger. The extrusion is shaped by the die and deposited onto a surface layer by layer to create a 3D object. Another method is to use a pellet extruder as the method of material deposition. In a pellet extruder, a screw serves as a feeding mechanism to transport and melt the pelletized material inside the barrel and force it out a heated die [25]. The pellet extruder offers more material flexibility and provides a stable process, whereas heating a large syringe could have degrading effects on the polymer over the course of a print. A screw extruder, on the other hand, is more complex compared to the other extrusion methods but due to its benefits, we adopted a screw-based extruder design.

Our proposed design is shown in Fig. 1. This design is similar to a standard industry-styled extruder, in a small form factor, used in injection molding. The design includes a hopper system to feed the correct material quantities, an extrusion screw to transport the pellets, an extrusion die to shape the material output, a drive motor, and the heating and cooling system. In order for all of these parts to seamlessly work together, a considerable amount of testing and analysis is required. As this is not a deterministic process, the printing platform must also be able to accommodate any unforeseen changes to the extruder design. Large-scale extrusion machines focus on many parameters to provide stability and accuracy. However, in our design, the two main parameters used to determine the working condition are temperature and pressure. One of the major design constraints for the extruder is its size; it needs to be small and light weight to allow easy integration with a low-cost scanning mechanism.

2.1 Hopper design

As noted earlier, most of the currently available FDM 3D printers utilize a filament as the feed material. This feeding method uses a gear to pinch the filament for grip and a stepper motor to accurately drive the filament and control the feed rate. Due to the uniformity in material input and a precise feed rate, the output becomes very consistent. While this feeding method is simple to realize, it is not free from issues. Occasionally, material can build up on the gear(s) which lowers the contact friction and can create slippage when pressing out the filament. A similar issue also occurs if too much heat builds up around the pinching mechanism and softens the filament.

Although pellet extrusion has been around for a long period of time, the implementation of it in 3D printing is currently very low. It is mostly due to the difficulty in obtaining a consistent extruded material from pellets. A simple reason is the material introduced to the extruder is hard to control in exact quantities. The pelleted material is held in a hopper

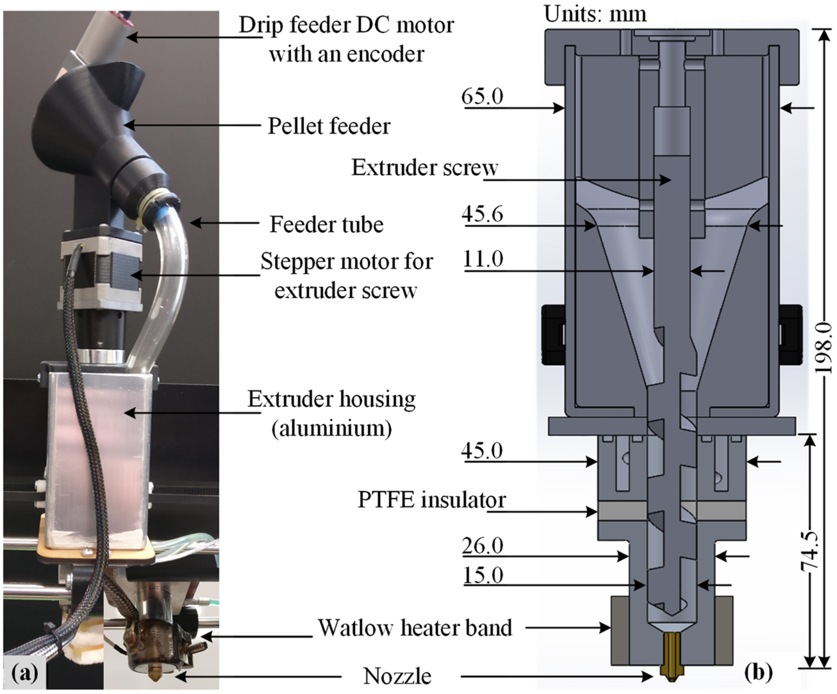


Fig. 1 **a** Pellet extruder with an integrated drip feeder and hopper. **b** CAD model showing the internal structure of the extruder and important dimensions

in the form of granular-sized pellets for the screw to push through the system. Commonly, the material is gravity assisted and in some cases the hopper is assisted by an agitator or stirrer. This is to help prevent poor pellet flow characteristics and remove any material sticking to the wall. To reduce any conveying problems, the hopper has been designed to be cylindrical in shape as a square hopper's corners could cause feeding issues. As this design has the screw in line with the hopper, the hopper acts more as a guide for the polymer to flow into the throat of the extruder.

2.2 Drip feeder design

Since the proposed extruder is mounted vertically, precise control over the amount of pellets fed into the hopper is necessary to avoid the hopper from jamming and inconsistency in the prints. Furthermore, since the screw passes through the middle of the hopper, if the hopper has too many pellets inside it, the large agglomerate acts like an insulation barrier preventing the rising heat from escaping. If this happens, the pellets soak up the heat and can end up sticking to each other forming large groups that have the potential to stall the screw or more commonly prevent the downward transport of material and eventually starving the extruder. In order to achieve a consistent flow of material through the primary hopper, the rate and quantity of material entering the system need to be controlled.

A drip feeder has been designed and added as a pre-step to the extrusion process (Fig. 1). The shape of the feeder is kept similar to the main extruder's circular shape to remove any edge effects and prevent possible flow restrictions. The feeding hopper uses an auger to transport the pellets at a fixed rate. The feeder is mounted above the extruder and the pellets are pushed out in small quantities at the rate required by the extruder.

2.3 Extruder screw design

The design of our pellet extruder is very similar in many ways to a conventional pellet extrusion process. It is a simple full-sized single-screw extruder miniaturized to work with a consumer-sized 3D printing platform. The extruder is vertically mounted with a drip 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. From the design point of view, the major part of the extruder is the screw used to transport the pellets to the heating region and push the molten material out of the nozzle to create a continuous bead for the printing process. Depending on the application, a variety of screw designs are available in the extrusion industry (Fig. 2). However, every aspect of a large-scale extruder is impractical to include in our design as the purpose is quite different from conventional use.

In the most common single-screw extruder designs, a screw with three sections is used for feeding, compression, and metering (Fig. 2a). The polymer in this case is prepared in the solid pellet form through a plasticating process which allows material shearing to generate heat and change the material viscosity before being extruded. The graph seen

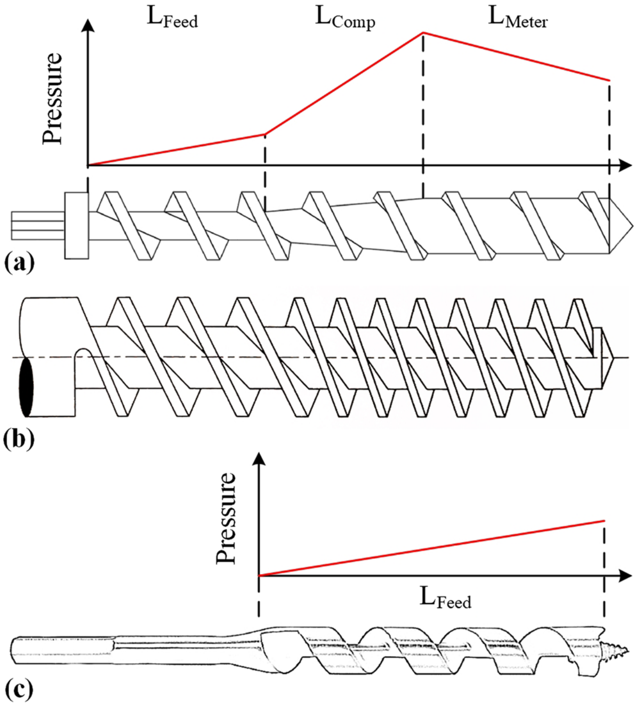


Fig. 2 Comparison of three extruder screw designs. A common three-section screw with its pressure profile (**a**), rubber extrusion screw (**b**), and an auger drill bit with it's pressure profile (**c**)

in the figure depicts a general representation of a pressure gradient caused through the die opposing material flow generated by the screw. There is a distinct compression zone (L_{Comp}) where the pressure increases rapidly along the screw. The total pressure calculation along the screw is the sum of the different zone pressures described by the following:

$$BackPressure = \triangle P_{feed} + \triangle P_{comp} + \triangle P_{meter} \tag{1}$$

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. 2c). 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 the following:

$$\triangle P_{feed} = \frac{dP}{dZ} L \tag{2}$$

with L being the length of the screw and dP/dZ being the pressure gradient over the length of the screw [4]. The result is a much lower pressure represented graphically in Fig. 2c. 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 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.

2.4 Heating and cooling system

The heating is applied to the extruder to heat and melt the polymer as an initial process before extrusion can begin. The heating is then monitored to maintain the correct extrusion temperatures. It is noteworthy that in larger scale extrusion systems, the screw is used to produce a majority of the heat through shear in the material. While in a smaller design like ours, heating comes from an external source.

There are several ways that heating can be applied to the extruder, but we selected an electric heating band heater (Watlow electric band heater with an external Watlow EZ-ZONE PID controller) due to its ease of use and controllable heating characteristics. Additionally, this type of heater allows for an easily adjustable range of temperatures with near to no maintenance and built-in temperature feedback. As the extruder is a miniaturized design, it closely resembles a consumer 3D printer design with one heated region right at the barrel end. This is contrary to a typical large-scale extrusion system where heating is applied in regions along the length of the barrel. Furthermore, our design requires a controllable output and the use of a screw that is heated at many places would not be practical.

While the heating is beneficial for the extrusion process, the upwards flow of heat through the screw and hopper is detrimental as it can partially melt the pellets and turn them into agglomerates. Therefore, a heat removal mechanism needs to be incorporated in the extruder design, even though the cooling is synonymous to wasting energy and lowering the efficiency of the whole process. In large production extrusion lines, cooling and energy loss can add up to a large portion of operating costs over a long period of time. Ideally, there should be minimal to no cooling throughout the process but due to the process restrictions, it is not possible and the proposed system is tailored to minimize energy loss as much as possible.

In the proposed design, we produce a fluid channel around the top neck of the extruder, where the hopper meets the barrel of the extruder, and pump a coolant fluid through it to remove the excess heat from the system. A closed loop control system controls the flow of the coolant to make sure that only excess heat is removed. Initially, air cooling was used but the heat extraction was insufficient in removing the propagating heat up the extruder. The compact design of the extruder necessitates fast heat removal to avoid heat traveling up the internal bore of the extruder and causing the pellets to stick to the hot surfaces and eventually blocking the system. Consequently, an automotive-grade coolant with a high concentration of glycol is used for an effective cooling. The boiling point of the coolant is important as it makes sure that the cooling pump does not have to be running all the time except when the temperature of the measurement surface goes above a set limit.

2.5 Printing platform design

Figure 3 shows the full printer and its components. This platform has been designed for robustness and ease of use with the extrusion system. The platform is a common XYZ cartesian design based on available open-source systems. All three axes have dual support cylindrical linear guide rails; the *Z*-axis is driven by two 400-mm Tr8*4 vertical lead screws and both *X*-axis and *Y*-axis are driven by GT2 belts. The stepper motors that drive the axes and the extrusion screw are all NEMA 17 size to fit the open-source design. With a light-weight system in mind, the choice of extruder drive motor becomes conflicted with weight versus power consideration. However, the motor needs to be both controllable and has the ability to extrude reliably. If the motor does not have enough torque, there is a risk that the friction of the polymer melt could overcome and stall it.

The extruder is mounted on two linear bearings and is movable across the *X*-axis. An alternative option is to have the extruder stationary and the printing bed moving in the 2D plane. The extruder is a vertical design allowing for a more compact layout where the pelletized material is poured in the top and output is extruded through the nozzle at the bottom. These features fit and operate in a similar manner to current small-scale FDM printers, allowing this system to use open-source software for the printer configuration and control. The printer control board is a RAMPS 1.4 [18] running on an Arduino Mega 2560 microcontroller and communicates to a computer over a serial port. The open source software used to configure and run the control board is Marlin [14].

3 Measurement, communication, and control

The implementation of the control system in any extruder design is one of the most important aspects. If there is an insufficient amount of control/monitoring, then there is a limited knowledge of what is happening throughout the system beyond the point which can be seen by the operator (or where any sensors may be mounted). Sensors common in the complex industrial extrusion systems monitor screw speeds, temperatures along the barrel, the die head pressure, power consumptions, and in some special cases vacuum pressure. The most important parameters for an extruder to maintain consistency are the temperature of the melt and the pressure generated for extrusion. If the melt temperature

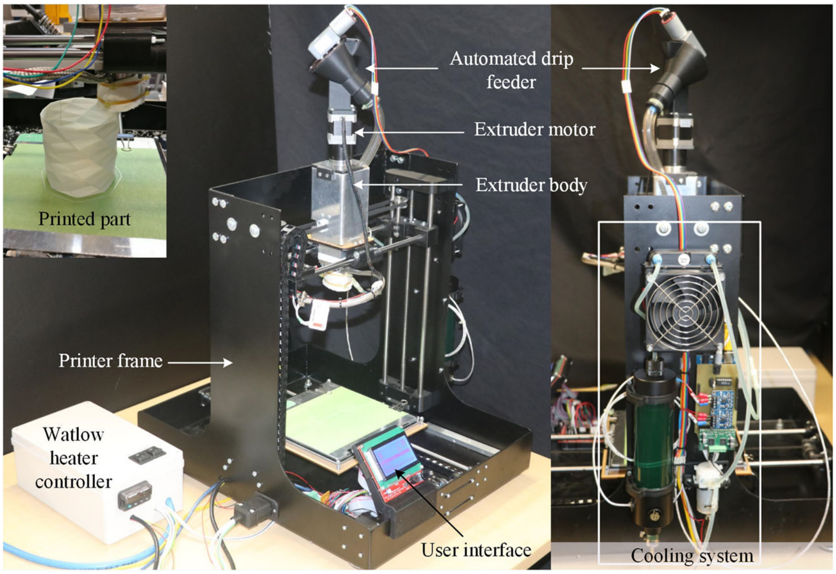


Fig. 3 Custom built biopolymer pellet printer

goes above or below the ideal value, the viscosity of the polymer output will change and potentially cause issues when printing.

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 fully refined and accurate, it becomes a lot harder to implement these measurements. Therefore, 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 screws focus rests on conveying the material into a heated melt zone and pushing it out of the extrusion tip. This adds a lighter load on the drive motor and provides greater control over it during a print. As the pellets are gravity fed, the pressures generated will be quite small in scale and quite erratic from printing behaviors. The inclusion of a pressure sensor would almost be of no use to the printing process as acting on fluctuations caused through printing behavior could result in wrongful actions. Therefore, the use of a pressure transducer has not been implemented into the design. To reduce inconsistencies, the screw speed is strictly set during printing using “Slic3r” software [17] to generate the g-code output. This allows the pellets to be transported in a controlled manner, and by monitoring and controlling the temperatures, a large improvement can be seen during testing.

With a fixed screw speed and monitored temperatures, the material is led into the melt zone at a constant rate, but in order for the extrusion output to be controllable, the infeed of material must also be controlled. When adding pellets to the extruder in large quantities, the extrusion output is only maintained for a short period of time before heating problems occur. Although the liquid cooling loop around the neck of the extruder keeps the heat from propagating up the barrel, heat is still able to rise through the screw and from inside the bore. With a large quantity of material in the hopper, the material becomes an insulator and slows down the heat escaping. This in turn prematurely heats up the polymer creating a block. It was observed that in smaller quantities, the process remained in a stable state throughout long periods of time. Therefore, a drip-feeding hopper was implemented as a means of controlling the quantity of material fed into the extruder over the course of a print. The main purpose of this controller is to reliably feed the correct quantity of material over time by roughly matching the quantity of material being extruded via a secondary auger screw. With a set speed for the primary extrusion screw on the test platform, the only other form of control needed is to detect a feeder blockage, which is done by reading the encoder signals on the dc drive motor. The controller reacts by reversing the feed screw for a short period to relieve the blockage before continuing. A flow diagram of the main components of the control system is shown in Fig. 4 while Fig. 5 shows a graphical user interface developed in Microsoft C# for the control and monitoring of the extrusion process.

The temperature control is implemented in the system to help reduce the fluctuations in the viscosity of the polymer output. There are several temperatures taken into account (Fig. 6): the temperature of the cooled barrel and the temperature of the circulating coolant. The heating band temperature or the melt temperature at the die is controlled by an external Watlow EZ-ZONE PID controller. The heating controller uses PID to manipulate the heating band and maintain a steady target temperature. In addition to

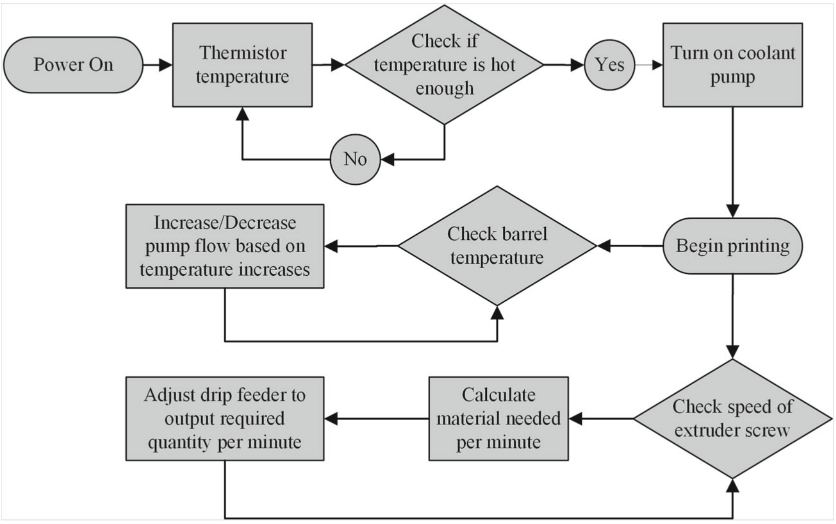
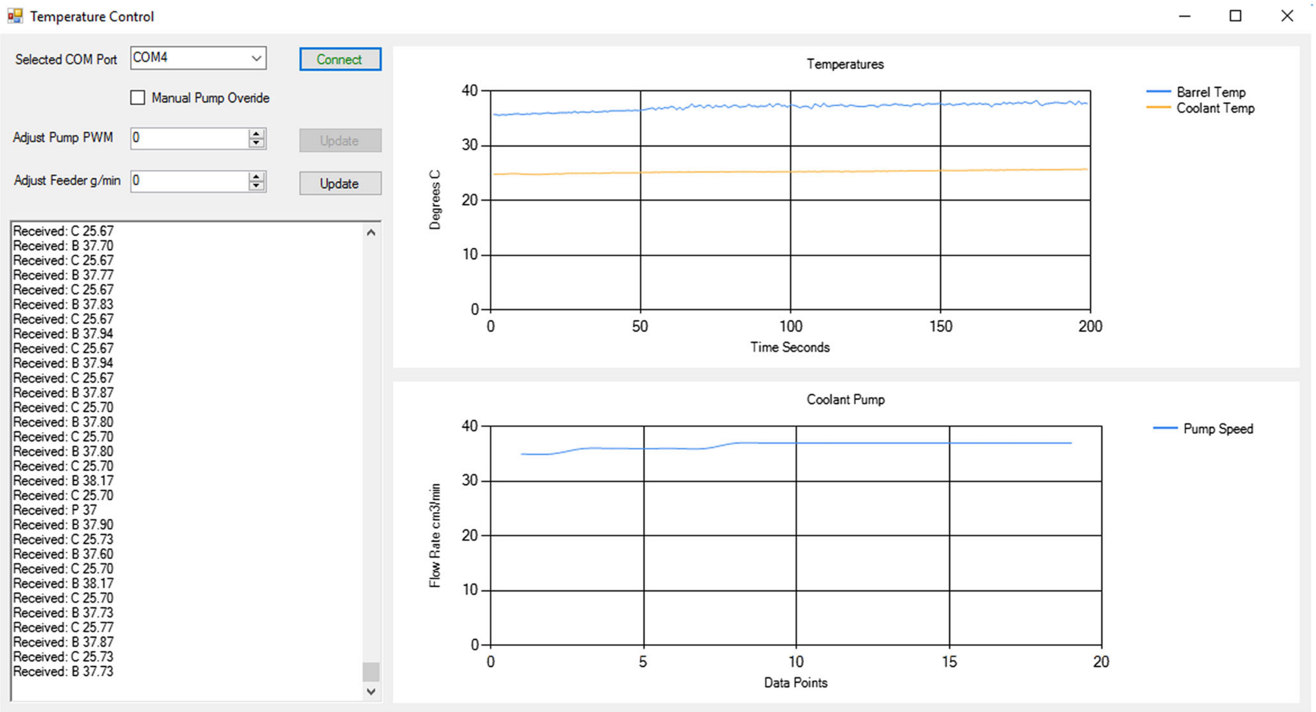


Fig. 4 Extruder control flow diagram



Selected COM Port: COM4

☐ Manual Pump Overide

Adjust Pump PWM: 0

Adjust Feeder g/min: 0

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Received: C 25.67
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Fig. 5 Extruder control graphical user interface

software methods of control, a second more recent extruder design has a polytetrafluoroethylene (PTFE) thermal barrier in between the barrel and liquid cooling block (Fig. 6). To further help with the heating isolation, a ceramic insulation padding is also wrapped around the heating band to lower heat transfer losses in the melt zone. Figure 7 depicts finite element analysis of the heat flow from the heating zone towards the cooling region. It is evident that the presence of PTFE insulator significantly reduces the heat transfer. As the

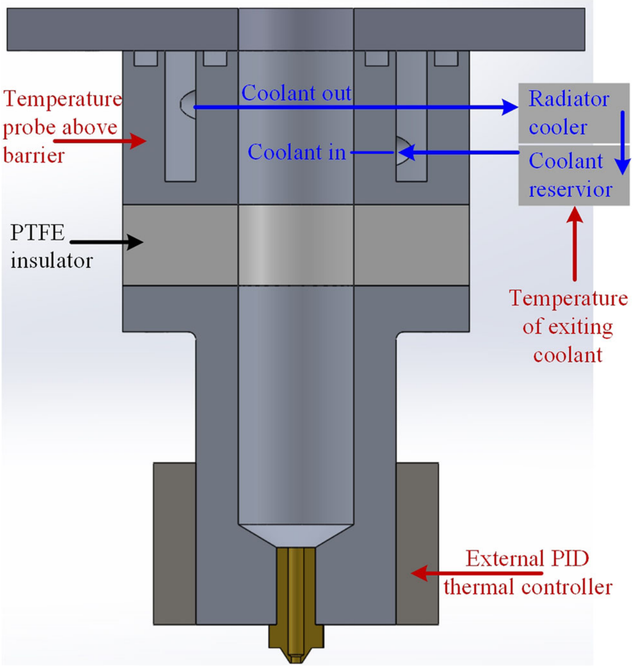

Fig. 6 Extruder temperature control and monitoring layout

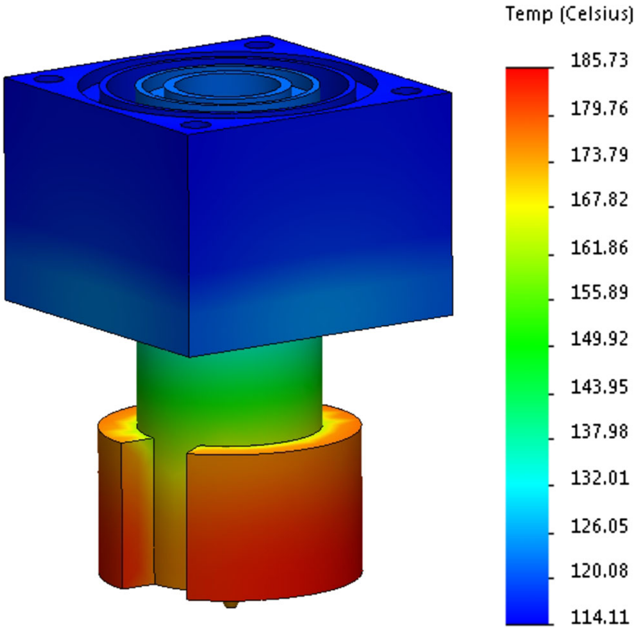

Fig. 7 Finite element analysis of the heat flow through the extruder

PTFE insulation cannot stop heat transfer through he screw, the use of liquid cooling is still necessary but the cooling system does not have to run for a long period of time.

4 Refinement of processes

4.1 Platform calibration

Once the platform was assembled to working condition, calibration of the axes is carried out in the control software (Marlin). The X, Y, and Z stepper motors were adjusted according to their steps taken versus the distance traveled. However, the extruder was very challenging to calibrate as it also required a value for steps per millimeter where it was expecting the material to be in filament form. Early on in testing with a standard hopper, the steps per rotation of the extruder screw did not correspond to the material output. Only a rough relationship between the drive motor steps and the 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 is also taken into account as the number of steps needs to be adjusted according to the ratio. 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. When the drip feeder was added and the feeding speed was calibrated, there was a dramatic impact on both the quantity and consistency of the output by the extruder. As the screw drive motor could only provide a maximum torque of 3 Nm, the speed changes across different aspects of the print process caused inconsistencies, and therefore, a constant speed was used.

The acceleration and jerk settings are defined inside the Marlin software to allow good control within the limits of the gantry system. The value of acceleration used for x-y-z and extruder movements during printing is 3000 mm/s^2, and for travel movements, a reduced value of 2000 mm/s^2 is used. The jerk control is set at 20 mm/s for x-y movement, 0.4 mm/s for z movement, and 5.0 mm/s for extruder movement.

4.2 Print preparation

Aside from the platform calibration, the output consistency comes down to several main factors that were previously discussed: the heating and cooling systems, the drive motor speed, and the quantity of material input to the extruder. The screw speed and material input were controlled based on the quantity output over time. The heating is set and maintained through a separate PID controller, and the cooling keeps the material from prematurely sticking to the extruder's surfaces before reaching the melt zone. Once a consistent output is achieved, there are several minute details to be addressed in order to maintain the quality of the printed parts. The biggest concern with PLA pellets is the moisture content absorbed by the pellets. A high moisture content is often the cause or linked to blockages, flow rate changes, and output variations where the extrudate expands. To eliminate this, the pellets are placed in a heated chamber at 70 °C for a minimum of four hours. The ambient room temperature is conditioned to between 23 and 24 °C, thus providing a steady environment. During testing, layers can curve or delaminate from the printing platform. To solve this issue, the bed is heated to 50 °C, just enough for the PLA to sufficiently meld with the platform. A skirt is also printed around the initial three layers to provide a sufficient amount of cooling in between each layer (Fig. 9).

Once the extruder heater reaches the required temperature, the coolant pump is activated and the extruder is run through for a short period (1–2 min) prior to printing in order to reach a uniform state. This needs to be done because the current design does not incorporate an inner barrel temperature monitoring device. If the material temperature is not fully developed, it will impact on the output flow rate and the platform feed rate will outrun the extrusion speed. To form an esthetic print, the printing parameters are tested, checked, and optimized according to the thickness of the output and the extrusion speed. Figure 8 shows a variety of parts with thin and thick sections printed using the developed system.

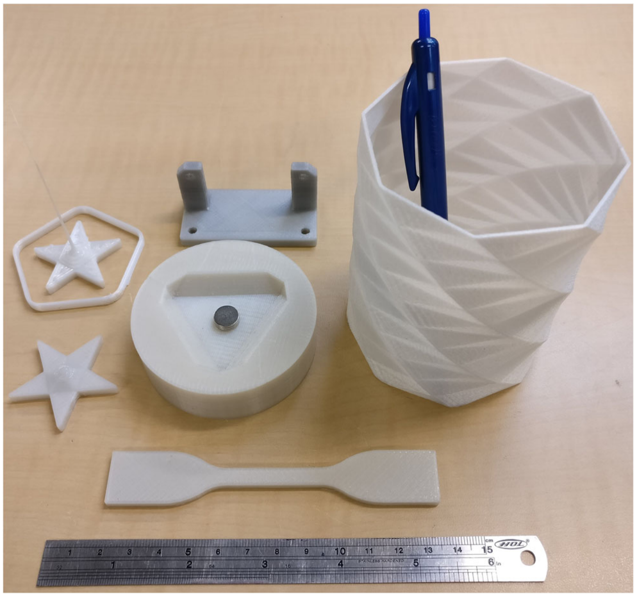

Fig. 8 A variety of printed parts demonstrating the capability of the designed pellet extrusion system

4.2.1 Effect of nozzle sizes

The heated nozzle (die) of the extruder is what shapes the output of the polymer and generates the pressure inside the extruder. The smaller the nozzle size, the more pressure the screw needs to apply to extrude the material. The initial system calibration and testing were carried out using a 1.5-mm-diameter extrusion nozzle and a consistent 1.4-mm-diameter extrusion was achieved at a 0.4-mm layer height with a 10-mm/s print speed. The nozzle diameter was then reduced to a 0.8-mm-diameter nozzle and the print speed was kept the same at 10 mm per second. After calibration, the observed output was a consistent 0.7-mm-diameter extrusion at a 0.2-mm layer height.

5 Testing and mechanical characterization

The testing and characterization was carried out using two different extruder designs to determine any print quality differences. On the most recent extruder design, the nozzle size is changed and the print speed is significantly increased to also determine if there are any material property changes in the process of extrusion from pellets.

5.1 Mechanical strength

The mechanical properties of the PLA samples were tested by printing sample groups according to the ASTM D638 type IV standard (Fig. 9). The samples were tensile tested using an Instron 5967 with a 30-KN load cell and a 10-mm Class B-2 clip-on extensometer.

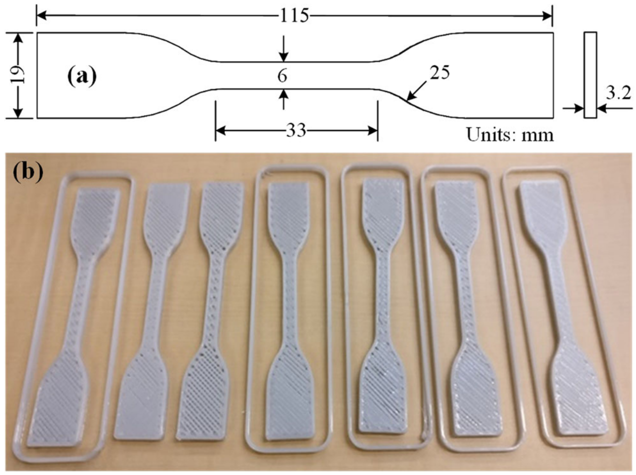

Fig. 9 **a** ASTM D638 Type IV specimen dimensions. **b** Specimens printed using different printer settings. The outer shell is added to give extra time for layer cooling experiments

Figure 10 shows tensile stress (MPa) versus tensile strain (%) of the different sample groups printed using settings given in Table 1. Each group has the same 100% solid infill and uses the 45° rectilinear pattern offered in Slic3r

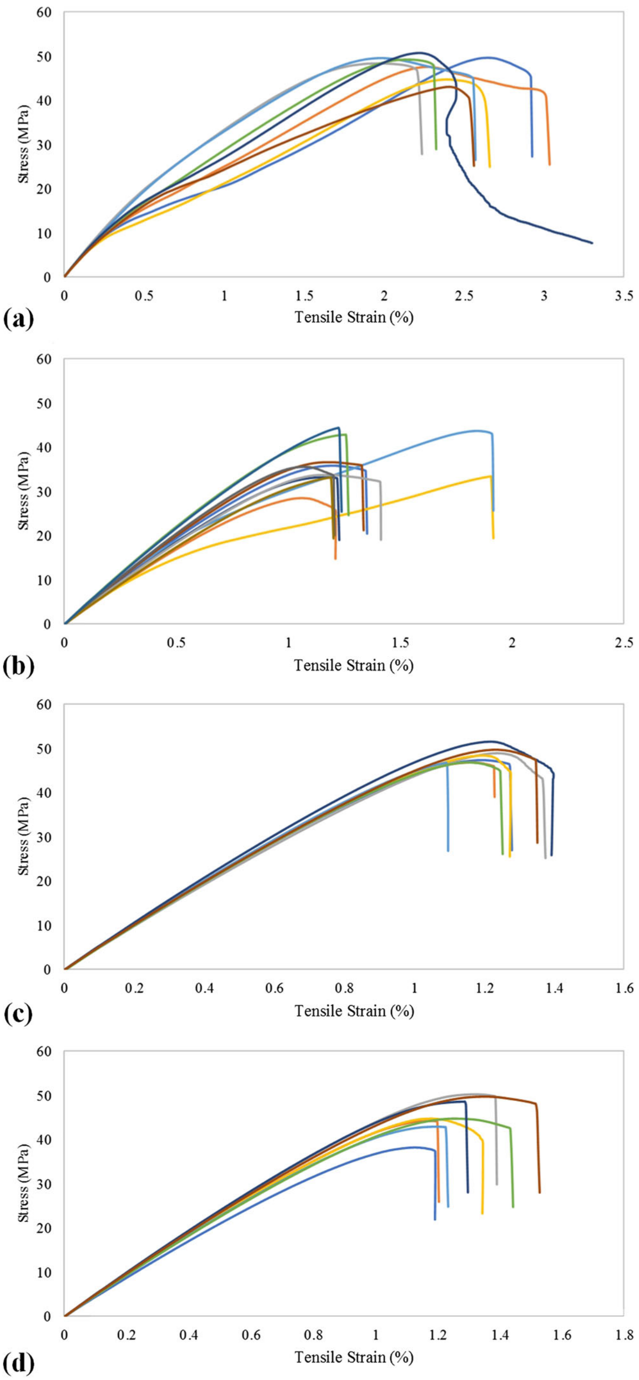

Fig. 10 Tensile test results for four sample groups as per Table 1. **a** For parts printed without PTFE thermal barrier, liquid cooling and 1.5-mm nozzle, **b** same as (**a**) with PTFE thermal barrier, **c** same as (**b**) with 0.8-mm nozzle, and **d** same as (**c**) but printed at a higher speed

Table 1 Print conditions

Extruder barrel type	Nozzle size (mm)	Print speed (mm/s)	Layer thickness (mm)	Output quantity (g/min)	Temp. setting (°C)	Barrel coolant type	Cooling temp. (°C)
Aluminum	1.5	10	0.6	0.8	185 ± 5	Glycol	52
Aluminum with PTFE thermal barrier	1.5	10	0.6	0.6	175 ± 5	Glycol/water	27/25
	0.8	12	0.2	0.18	175 ± 5	Glycol/water	27/25
	0.8	30	0.2	0.2	175 ± 5	Glycol/water	27/25

version 1.2.9. The first sample group (Fig. 10a) used the extruder without the PTFE thermal barrier and a 1.5-mm nozzle extruding at 10 mm/s. The second group moved to the most recent extruder design using the thermal barrier and keeping the other settings same as for the first group. The third sample group shows the change from a 1.5-mm to a 0.8-mm nozzle. The extrusion speed also needed to be increased from 10 to 12 mm/s as the scaled polymer settings decreased the extrusion rate too far; this caused the polymer to occasionally overheat and decrease the viscosity. The last sample group was built using the 0.8-mm nozzle, but the extrusion speed was increased to 30 mm/s.

5.2 Discussion of results

The results given in Figs. 10 and 11 show consistent mechanical properties and support the utility of pellet-based extrusion for 3D printing. The first and second groups of samples were to compare the material properties between the two extruder designs. The first sample group produced a fairly consistent fracture stress grouping around 50 MPa but because of the heat stabilization in this extruder design, the polymer melt temperatures were inconsistent throughout the prints. The second sample group shows a reduction in the maximum stress at fracture. The inconsistencies seen and the overall lower tensile stress can be attributed to the extruder being freshly machined (not worn out). The tolerances inside the extruder were not ideal when accounting for the material swelling during heating. This caused the screw to rub inside the bore which greatly affected the material flow and melt viscosities at different stages of the print. By the time third and fourth sample sets were printed, the extruder was already worn to a more consistent operating condition. Therefore, the maximum stress for both sets came out around 50 MPa which is comparable to commercially successful open-source printers [24]. In these groups, the variations among the samples are also minimal which indicates a high degree of consistency and repeatability of the printing process.

It is well-known that the mechanical strength in FDM depends on the bonding of the extruded filament (or roads) [10, 21]. 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 tabletop SEM (Hitachi TM3030Plus). The imaging samples were cut from the printed specimens without any surface modifications and low voltage (5 kV) imaging mode was used to avoid charging artifacts. For the sake of comparison with the commercially available filament-based FDM printers, PLA specimens like the ones shown in Fig. 9 were printed on an UP mini printer and imaged the same way as the pellet extruder specimens. It is evident from Fig. 12a, b that the conventional printer produced a wavy surface and large-sized voids near the boundary. These voids are typically found in FDM parts and have been reported in the literature by many researchers [1, 26]. However, the pellet extruder gave a smooth surface and left very small voids (Fig. 12c, d), if any. Furthermore, the roads appear to be closely laid compared to the filament printer, where the longitudinal voids can also be easily seen. The lack of these voids results in the superior mechanical strength evident

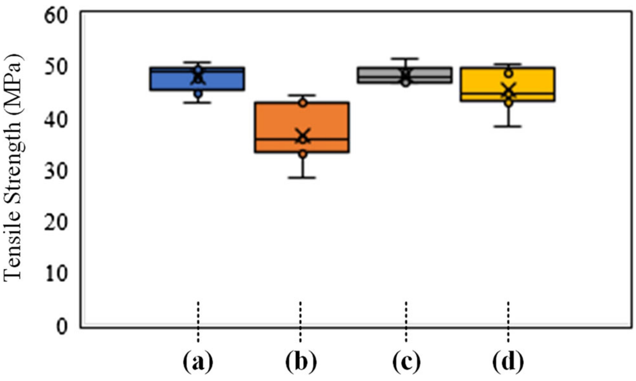

Fig. 11 Comparison of tensile strength for data shown in Fig. 10. The labels on *X*-axis refer to the corresponding parts of the Fig. 10

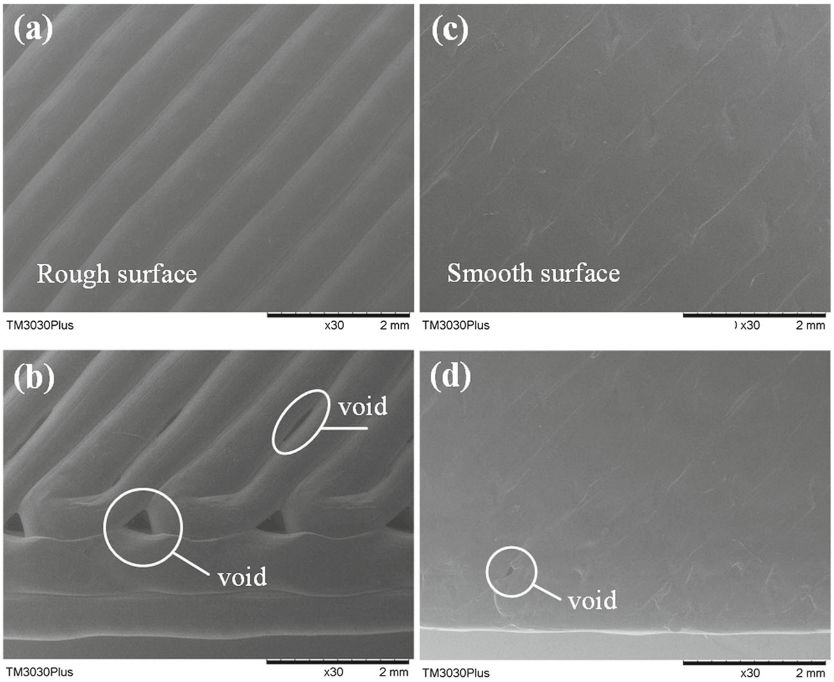

Fig. 12 Topographical images of PLA specimens produced on a conventional filament-based FDM printer (**a**, **b**) and printed using the pellet extruder (**c**, **d**)

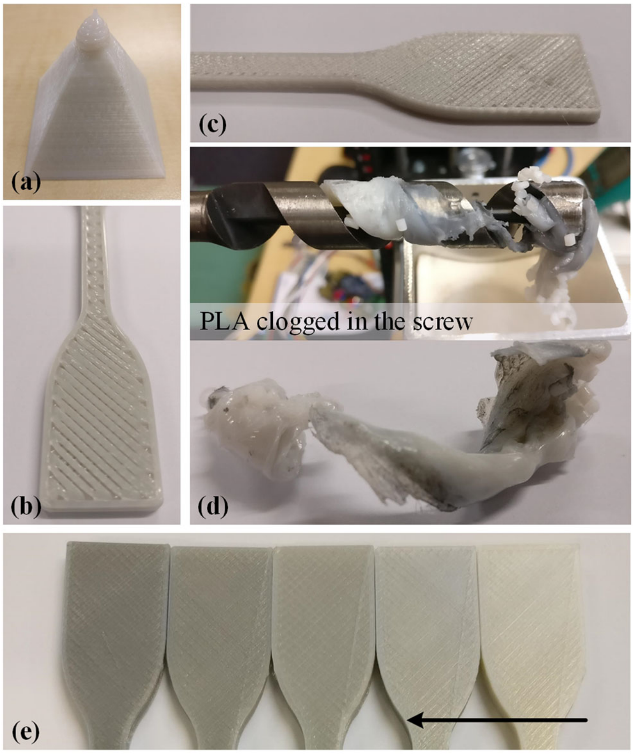

Fig. 13 Problems found during the course of development and optimization of the extrusion system. **a** Lack of rapid layer cooling resulted in a material blob, **b** improper filling, **c** inconsistent bonding on the build surface, **d** material clogging in the screw, and **e** color change due to aluminum contamination from the extruder walls

from the tensile tests. The overall surface quality of the parts also appears to be better than the conventional counterpart due to the lack of waviness and voids.

6 Conclusions

We have successfully developed an extrusion system that allows the 3D printing of pellets with similar consistency and strength as found in the commercially available printers of the same class. The innovative design of the extruder resulted in a compact and light-weight unit that can be mounted on an 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 esthetic quality and shine of the parts are much superior to 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, in no way is the presented system devoid of problems and limitations. Figure 13 shows various issues including the clogging of the screw with the print material, improper filling, inconsistent bonding, and color change of the printed material due to the contamination of the extruder material with the print material.

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 heating and cooling effects on the system can help with better control over the heat flow. Similarly, there is a need of pressure transducer to determine if the correct pressure is obtained before turning on the drip feeder. If this is not possible, another approach would be to use some form of vision processing to determine if the output extrusion is of adequate thickness/diameter.

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