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3-D Printable Polymer Pelletizer Chopper for Fused Granular Fabrication-based Additive Manufacturing

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Abstract: Although distributed additive manufacturing can provide high returns on investment the current markup on commercial filament over base polymers limits deployment. These cost barriers can be surmounted by eliminating the entire process of fusing filament by 3-D printing products directly from polymer granules. Fused granular fabrication (FGF) (or fused particle fabrication (FPF)) is being held back in part by the accessibility of low-cost pelletizers and choppers. An open-source 3-D printable invention disclosed here provides for precise controlled pelletizing of both single thermopolymers as well as composites for 3-D printing. The system is designed, built and tested for its ability to provide high tolerance thermopolymer pellets from a number of sizes capable of being used in a FGF printer. In addition, the chopping pelletizer is tested for its ability to chop multi-materials simultaneously for color mixing and composite fabrication as well as precise fractional measuring back to filament. The US$185 open-source 3-D printable pelletizer chopper system was successfully fabricated and has a 0.5 kg/hr throughput with one motor, and 1.0 kg/hr throughput with two motors using only 0.24 kWh/kg during the chopping process. Pellets were successfully printed directly via FGF and indirectly after being converted into high-tolerance filament in a recyclebot.

Keywords: 3-D printing; additive manufacturing; distributed manufacturing; open-source; polymers; recycling; waste plastic; extruder; upcycle; circular economy

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1. Introduction

Adopting an open-source model of technological development by the founding members of the self-replicating rapid prototyper (RepRap) 3-D printer [1-3] community radically reduced the costs of additive manufacturing (AM). With the costs of prosumer (producing consumer) desktop 3-D printers dropping low enough, the phenomenon of distributed manufacturing with AM emerged [4-6]. Using commercial polymer filament 3-D printing enables prosumers significant savings over purchasing of mass-manufactured products such as glasses [7], alternative energy mechanical parts [8], flexible products [9], toys and games [10], and a wide range of other consumer products [11,12]. The business community recognizes the potential shift in manufacturing with AM [13-15] because of millions of freely shared digital design files for 3-D printable products [12]. A high return on investment (ROI) is found for prosumer distributed manufacturing with commercial polymer 3-D printing filament based on downloaded substitution values [16,17]. These savings are somewhat muted by the markup on commercial filament over base commercial polymers, which is currently about five to ten times the cost of the raw plastic pellets. This reduces deployment of distributed

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manufacturing to accelerate the adoption of AM at the prosumer level [18] as well as limiting the vast majority of 3-D printed articles to small objects.

One method of overcoming these cost barriers is to skip the entire process of fusing filament into a 3-D printed object by printing directly from polymer granules. Fused granular fabrication (FGF) or the more generic fused particle fabrication (FPF) (indicating any size or shape of polymer feedstock) has been developed and designs are flourishing in maker communities [19-21] as well as in industry with commercialized printers [21-26]. Academia has also taken a keen interest in the technology [27,28] for virgin [29] and recycled materials [30,31] including multi-head [32], industrial robot adaptations [33], electronics printing [34], flexible materials printing [35], and biopolymer printing [36]. To date, however, only a small subset of the thermoplastic materials capable of being printed by such systems have been investigated and there has been almost no research into printing with the nearly unlimited variety of obvious composited 3-D printing materials [37].

Potential applications available from coupling materials science with FGF is being held back in part by the accessibility of low-cost pelletizers and choppers. In general, these are large industrial machines not conducive for research or prosumer use because of their high throughputs and capital costs. There have been some attempts at making such systems on the small scale by the maker community [38-41]. These systems have several deficiencies. First, with current solutions, the feed rate is fixed at a constant speed meaning the size of the granules cannot be changed. The current solutions also only allow one inlet for filaments, meaning you can only chop one type of filament at a time. The throughput of material can be slower as well, because of the single input on the currently available machines.

In order to provide a low cost tool for making precise chopped pellets of both single thermopolymers as well as composites this study follows the open-source hardware design paradigm [42,43]. It thus provides open-source designs of a 3-D printable polymer pelletizer chopper for FGF-based AM. The system is designed, built and tested for its ability to provide high tolerance thermopolymer pellets from a number of sizes capable of being used in a FGF printer. In addition, the chopping pelletizer is tested for its ability to chop multi-materials simultaneously for color mixing and composite fabrication as well as precise fractional measuring. The results are presented and discussed.

2. Materials and Methods

2.1 Designs

The bill of materials (BOM) summary can be seen in Table 1 and the tools and consumables are shown in Table 2. As Table 1 shows a single motor version of the system can be fabricated for US$185. A more detailed BOM along with the STP (STandard for the Exchange of Product files for redesign in FreeCAD) and STL files (Standard Triangle Language file for direct 3-D printing on any RepRap-class FFF 3-D printer) are available in the Open Science Framework [44]. All STL parts unless specifically labeled to be printed with NinjaFlex can be printed with PLA or any other hard FFF thermoplastic.

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Table 1. *Bill of Materials for 1 motor setup*

Part	*Quantity*	*Price*
Drill motor	*1*	$99.00
PLA filament ~400g	*1*	$10.00
NinjaFlex filament ~ 20g	*1*	$1.60
12V DC motor 200 rpm	*1*	$14.99
Caster bearings	*3*	$2.99
Speed controller	*1*	$8.45
Power supply	*1*	$15.84
1" Forstner bit	*1*	$11.75
18 AWG hookup wire pack	*1*	$14.99
3/8"-16 x 1.25in bolt	*1*	$0.32
3/8"-16 regular hex nut	*1*	$0.05
M3 hex nut	*3*	$0.03
M3 grub screw	*3*	$0.29
M3 heat insert	*20*	$2.46
M5 heat insert	*4*	$0.91
M3 X 10 screw	*25*	$1.36
	Total	$185.03

Table 2. *Tools and Consumables*

Description	*Use*
5-gallon bucket or tote	Pellet collection
3-D printer	Part manufacturing
Zip ties	Wire management
Super glue	Mounting Ninjaflex to bearings
Wire strippers (10-18 AWG)	Stripping motor, controller wires
Electronic solder	Soldering wires to motor
Soldering iron	Heat set inserts and wire soldering
Heat shrink tubing	For covering solder joints on motor
Adjustable wrenches	Tightening 3/8" nuts
Micro screwdriver set	Screwing wires into terminals
Allen wrench set (hex key)	For m3 bolts, and m3 grub screws

2.1.1 Mechanical

3-D printable parts were manufactured on a Lulzbot Taz 6 (Aleph Objects, Loveland, Co) with 50% fill for PLA and 100% Ninjaflex (Ninjatek, St. Manheim, PA). After 3-D printing all of the STLs located at [44] with a RepRap class 3-D printer from NinjaFlex (for gripping wheels) and PLA (all other parts), and purchasing the components in Table 1, assembly can begin. In order to comply with open-source hardware design guidelines detailed assembly instructions are provided in this section. The mechanical assembly can be guided by a rendering of the major components shown in Figure 1.

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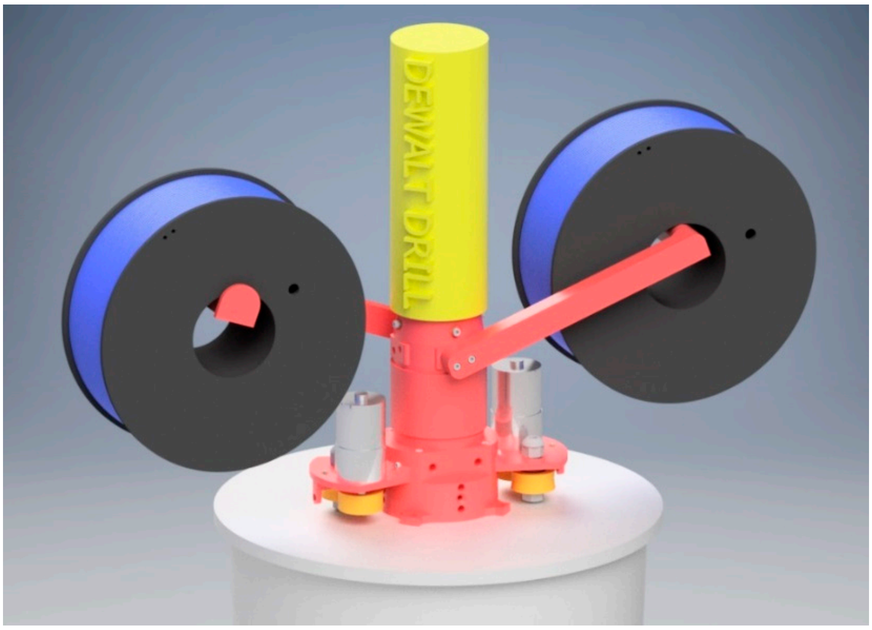

Figure 1. Rendering of major components of the 2x version of the open-source 3-D printable pelletizer chopper.

Filament is fed through Ninjaflex gripper wheels into the main assembly where it is chopped by the Forstner bit driven by the drill motor. The size of the pellets is controlled with the speed controller governing the NinjaFlex wheels and the motor.

The basic mechanical assembly instructions:

1. Subassembly preparation for grabbing wheels.
    a. Glue Ninjaflex wheels to double stack of bearings
    b. Glue Ninjaflex wheels to printed motor wheel
    c. Place M3 nuts and M3 grub screws intro printed motor wheel as shown in Figure 2.

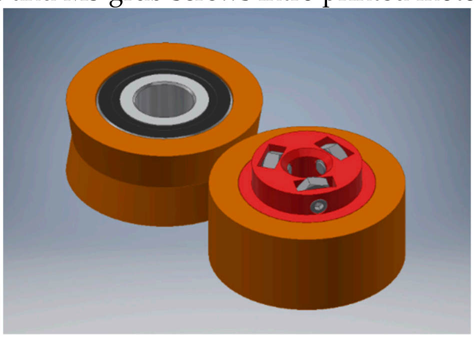

Figure 2. Rendering of Ninjaflex grabber wheels with nut traps and bearings.

2. Base Layer
    a. Start with the base part facing down (Figure 3), insert an M5 heat insert into the holes you plan on using.

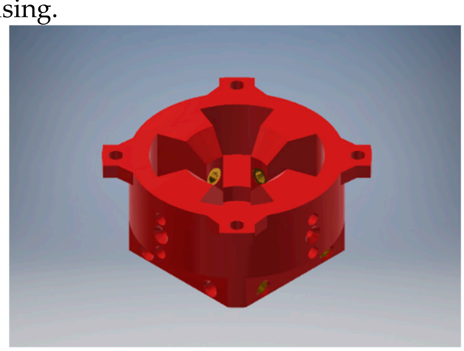

Figure 3. Rendering of base of the open-source 3-D printable pelletizer chopper.

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   b. Flip the base over and insert M3 heat inserts into the sides and top. Only insert where needed (e.g. One motor only needs one side, four motors need all sides)
   c. Once complete (Figure 4), insert bearing into the top as shown, then insert Forstner bit through the bottom

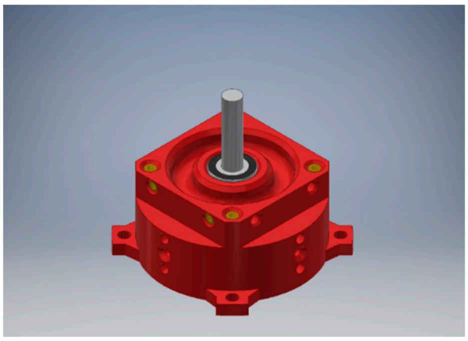

Figure 4. Rendering of assembled base of the open-source 3-D printable pelletizer chopper.

3. Middle Layer
   a. Place middle section on top of base, secure using m3 x 10 mm screws.
   b. Insert m3 heat set inserts into the top four holes, and the angled holes for the spool holders (Only need to insert into sides being used).
   c. Make sure the Forstner bit is through both the middle and the base as in Figure 5.

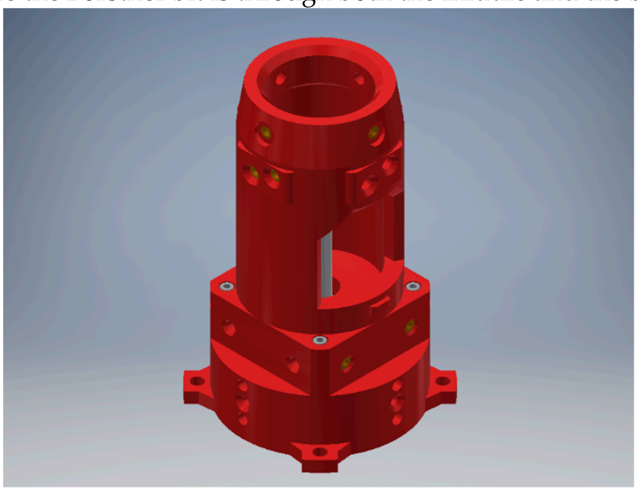

Figure 5. Rendering of middle section of the open-source 3-D printable pelletizer chopper.

   d. Put drill motor in through the top and use included chuck key to tighten onto Forstner bit (Figure 6).

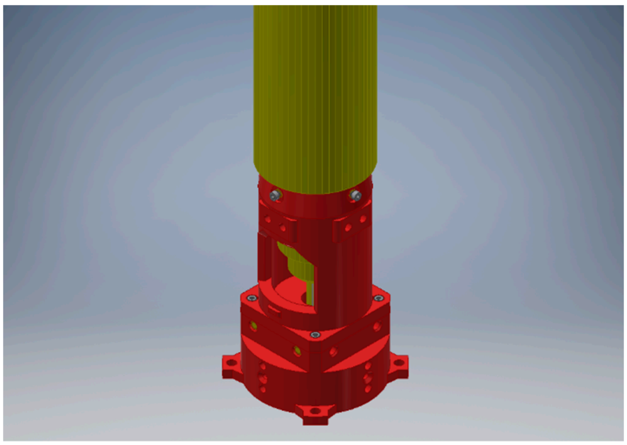

Figure 6. Rendering of assembled middle section of the open-source 3-D printable pelletizer chopper.

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4. Filament Drivers
    a. Screw motor into the bracket using m3x10mm screws, then place the printed motor wheel onto the shaft.
    b. Screw in the filament guide using an m3x10mm screw and heat set insert as shown in Figure 7.

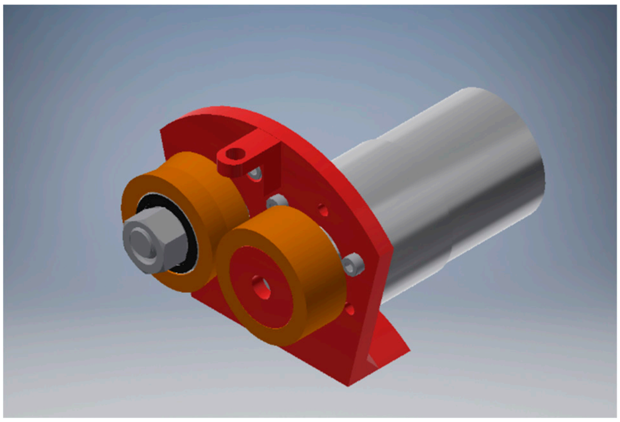

Figure 7. Rendering of filament driver of the open-source 3-D printable pelletizer chopper.

    c. Assemble the idler wheel by the following sequence: Bolt head, bracket, printed spacer, NinjaFlex wheel, and nut.

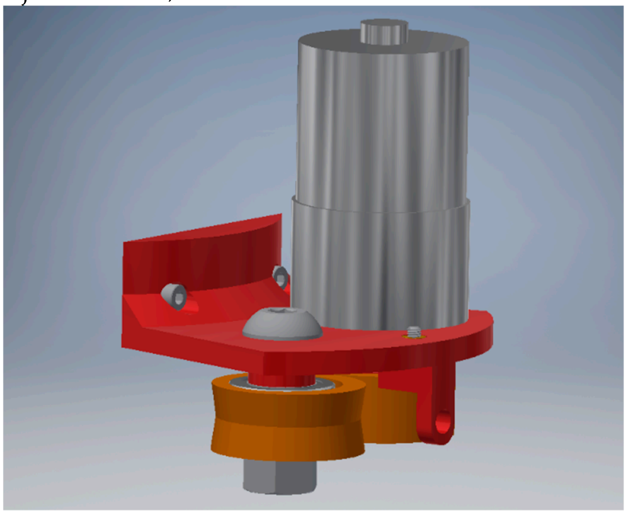

Figure 8. Rendering of the assembled filament driver with motor of the open-source 3-D printable pelletizer chopper.

    d. Secure filament driver assembly onto the rest of the main assembly as shown in Figure 8.

5. Spool Holder
    a. Use m3x10 mm bolts to attach the spool holder arms (Figure 9).

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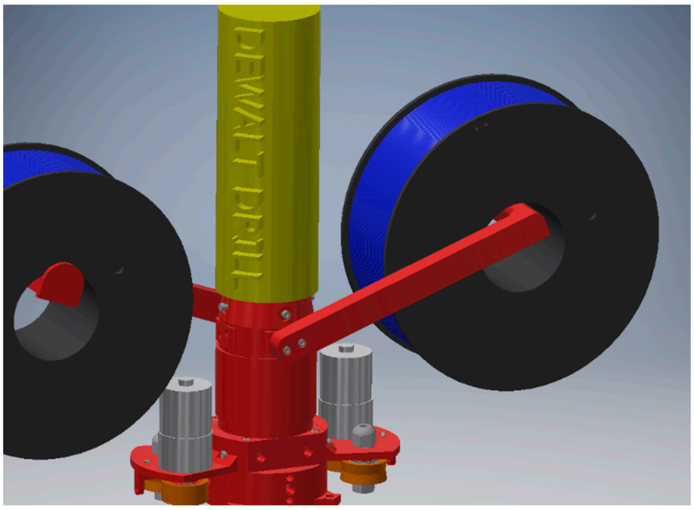

Figure 9. Rendering of the details of the spool arms of the open-source 3-D printable pelletizer chopper.

2.1.2 Electrical

Figure 10 shows the wiring schematic for the open-source 3-D printable pelletizer chopper.

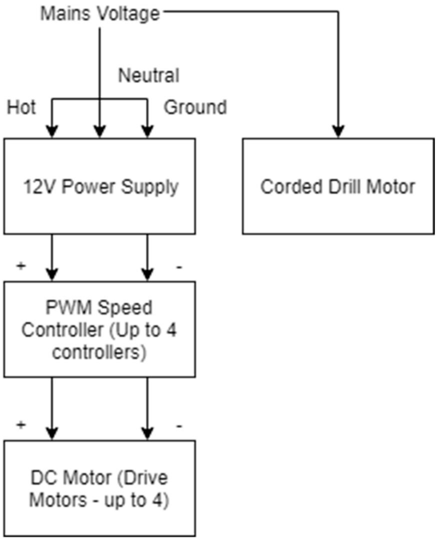

Figure 10. Pelletizer wiring schematic.

2.2 Materials

For testing, 1.75 mm polylactic acid (PLA) from Matterhackers, 1.75mm acrylonitrile butadiene styrene (ABS) from Matterhackers, 2.85mm PLA and ABS from Ultimachine were used.

2.3 System Performance Quantification

The size characteristics of the particles for each starting material as a function of drive speed from 200RPM to 100RPM to 50RPM were quantified using digital imaging and the open-source Fiji/ImageJ [45].The rate of pellet production (kg/hour) was timed with a digital watch and determined with an electronic scale (+/- 0.05). Electricity consumption was monitored with a multimeter (±0.005 kW h) for each material during processing.

2.4 FPF 3-D Printing

A prototype Gigabot X [46,47] was used to print the materials. 3-D models were sliced with Slic3r [48] and the printer was controlled with Marlin Firmware [49].

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2.5 Pellets as Recyclebot feedstock

A RepRapable recyclebot [50] (an open-source waste plastic extruder [51,52]) was used to make PLA filament from pellets. The extrusion temperature was set at 170°C with cooling enabled at 100% and a fixed puller rate.

3. Results

The open-source 3-D printable pelletizer chopper system was successfully fabricated as shown in Figure 11 and operated as demonstrated in supplemental video 1. It has a 0.5 kg/hr throughput with one motor and 1.0 kg/hr throughput with two motors. Electricity consumption was found to be 0.24 kWh/kg during the chopping process with 2 motors. It should be noted that the power draw from the feeder motors did not have an impact on energy utilization of the entire device.

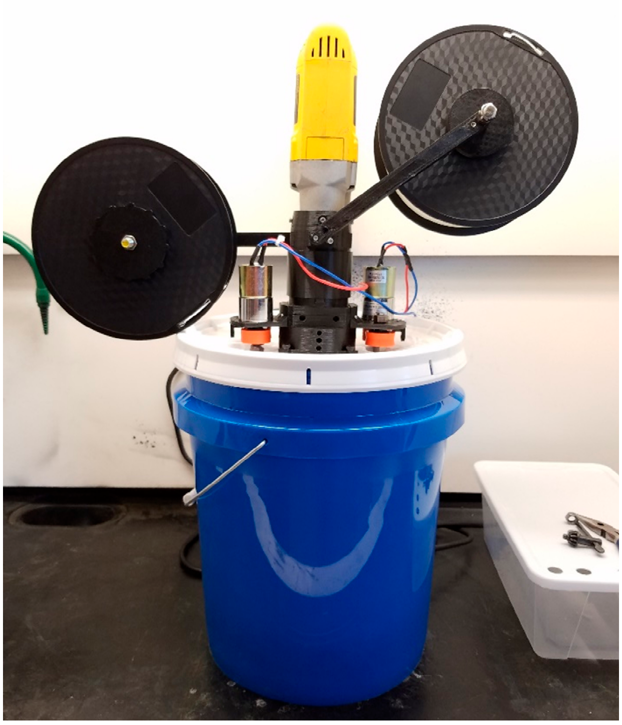

Figure 11. Fully assembled open-source 3-D printable pelletizer chopper system.

3.1 Pellet Manufacturing

The system could control the particle size by changing the speed. The particle size distributions are shown in Figure 12.

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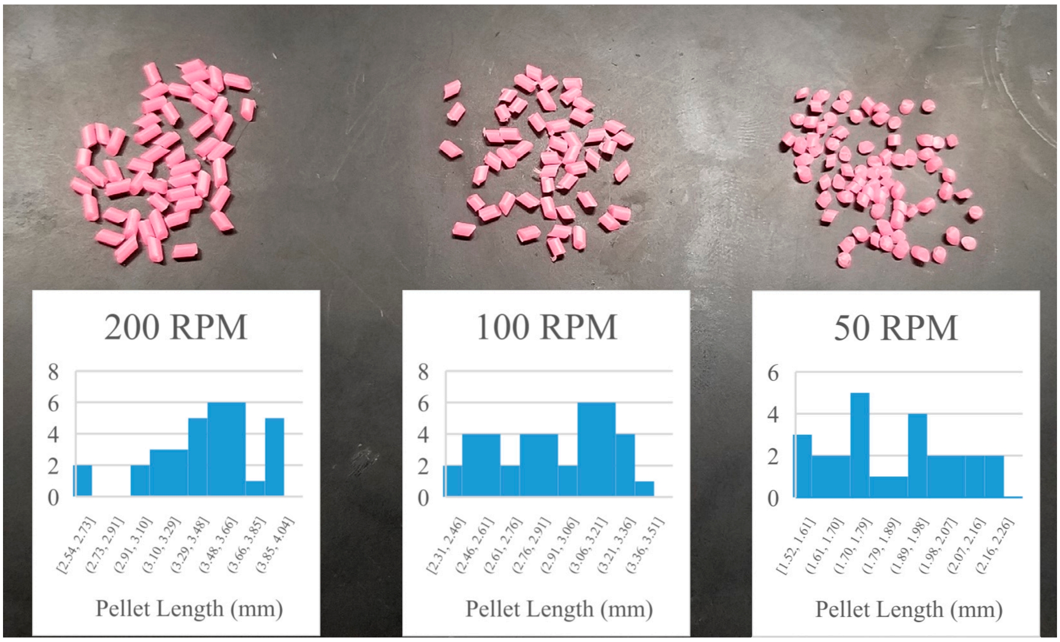

Figure 12. Photograph of particle sizes for 200, 100 and 50 RPM with the particle size distributions shown in the inset.

A graph of the mean particle size and the speed of the system is shown in Figure 13.

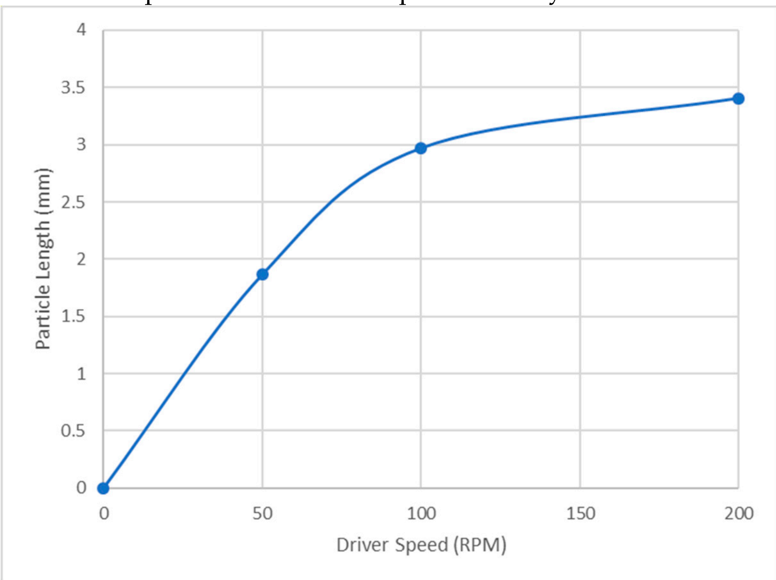

Figure 13. Mean particle size as a function of the speed of the filament driver.

The pellet production rate in kg/hr is function of speed of the motor and is linear: 0.5 kg/hr at full speed 1 motor, 0.25 at 100 rpm and 0.125 at 50 rpm.

3.1.1. Pellets for FGF

PLA pellets (Figure 14a) were fed into the prototype Gigabot X and no issues were detected during the printing process (Figure 14b). The small size, and cylindrical shape of the uniform pellets made it very easy to flow through the hopper and down into the extrusion screw.

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(a) **(b)**

Figure 14. a) PLA pellets made with the pelletizer b) printing with ease on the Gigabot X.

3.1.2 Pellets for Recyclebot

The results from making filament from the pelletized PLA are shown in Figure 15. Feeding into the hopper was consistent and no issues occurred during the filament extrusion process. The filament came out with a diameter of 1.75mm +/- 0.10mm which is the same result when using the virgin PLA pellets from NatureWorks LLC.

Figure 15. Example filament with a diameter of 1.75mm +/- 0.10mm made from RepRapable recyclebot from pelletized filament shown in bag.

3.2 Fractional Control of Color and Composite Mixing

Multi materials can be chopped simultaneously as shown in supplemental video 2.

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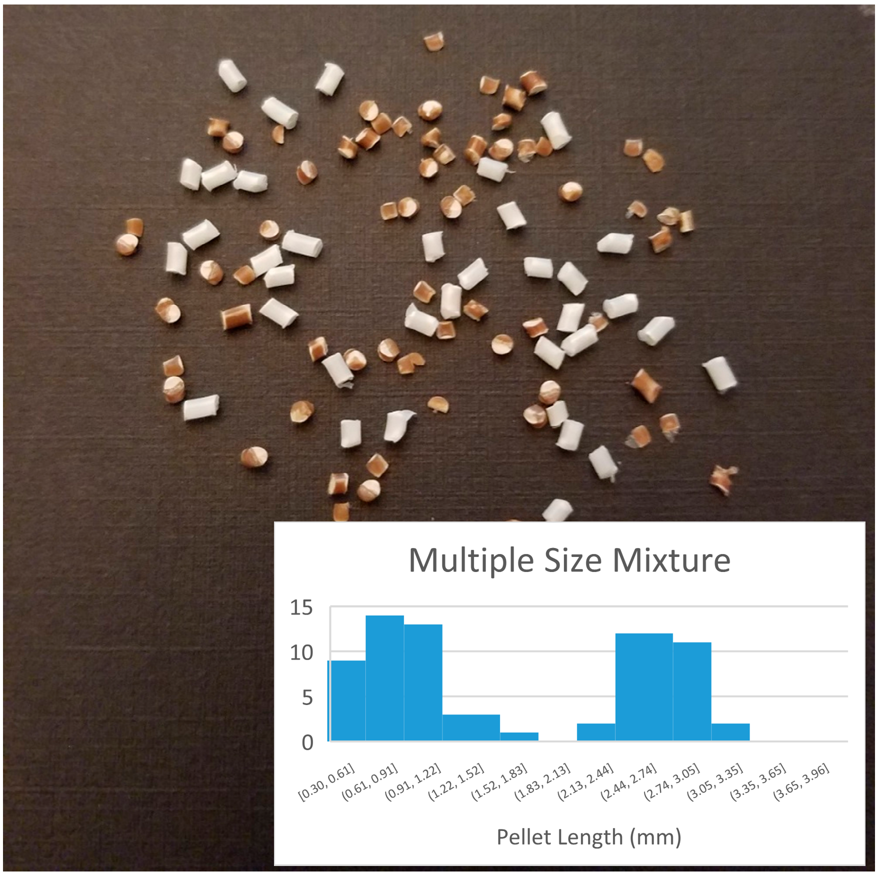

Figure 16. Image analysis of multiple size palletization demonstrated with large (white) and small (brown) filament.

In addition, the system can do multi material size chops as shown in different size distribution in Figure 16 to change color or other properties using mixing in the composition.

4. Discussion

4.1 Pellet manufacturing

4.1.1. Pellets for FGF

There were no issues with feeding the pellets into the hopper or having the auger push the pellets into the barrel of the Gigabot X. This process could be used when trying to extrude ground up plastic flakes or chunks to convert them into more uniform shape for better feeding into the auger such as was done by Pringle et al. for waste wood-PLA composites [66]. Each time a polymer is heated and extruded (whether in the recyclebot filament making process or during conventional fused filament fabrication (FFF)/ fused deposition modeling (FDM) 3-D printing) the mechanical properties of the thermopolymer are degraded [53-56]. FGF reduces the number of melt-solidify cycles a polymer must go through to get to a finished product. Thus, FGF printing has advantages of better economics and environmental footprint than conventional FFF 3-D printing [30,31].

4.1.2 Pellets for Recyclebot Filament Manufacturing

3-D printing with filament is still by far the most widespread method of AM [18]. Thus, this is a form of downcycling [57] that is acceptable for about five cycles [53,54]. To maintain acceptable mechanical properties, the recycled filament must be blended with virgin materials or reinforce with

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more robust materials. Despite these drawbacks, life cycle analysis of materials processed with a recyclebot found a 90% decrease in the embodied energy of the filament compared to traditional filament manufacturing [58-60]. Thermopolymers already demonstrated to be acceptable to the recyclebot process include successfully recycled as single component thermoplastic filaments such as polylactic acid (PLA) [50,53,54,61,62], high-density polyethylene (HDPE) [52,63,64], acrylonitrile butadiene styrene (ABS) [64-66], elastomers [9] as well as composites like waste wood biopolymers [67] and carbon fiber reinforced plastics [68]). With commercial versions of recyclebots becoming more prevalent [51] there is an opportunity to drive a tighter loop for the circular economy [60]. The system here was shown to be able to produce pellets for the recyclebot, which could be used for making composites and altering the properties of filament (e.g. change color).

4.2 Fractional Control of Color and Composite Mixing

However, producing pellets from these systems for complex composites like waste wood biopolymer composites [67], provide an even larger ecologically beneficial opportunity. The device disclosed and characterized supports this aim. So for example in an industrial or quasi-industrial granulator [69] is used to make flakes or chips it can be converted to low-quality filament, which can then be subsequently chopped by the invention discussed here and then converted to high-quality 3-D printing filament. This filament can be tuned for specific properties like those needed for scientific hardware [70-73]. This becomes important as manufacturers begin to disclose the materials they are made from [74] in order to facilitate recycling and/or market opportunities from consumers understanding the material ingredients that make up their products. Some countries like China already aid more aggressive recycling by having a detail-rich recycling code system and this has already been adapted to the 3-D printing community [75]. The invention of the open-source 3-D printable pelletizer chopper system can speed research and development in these areas. Also, in large scale niche 3D printing markets, the need for more material in the printer is essential to cutting out human intervention for changing out empty spools. When changing over to pellet fed systems, huge hoppers full of pellets can be stored next to the printer, with simple vacuum systems used to feed the printer as needed. This solution removes the need for large, 8-10 kg spools, which cause strain on the extruder motors for large 3-D printers and can almost provide an endless source of feedstock [76]. These features generally enable the technical and economic potential of large-scale polymer 3-D printing.

4.3 Future Work

This study investigated both single- and double-line use of the open-source 3-D printable pelletizer chopper system. This is adequate for matching the majority this generation of polymer 3-D printing available on the market (e.g. colorants or simple composites like glitter or glow-in-the-dark filaments). The current design can hold up to 4 incoming lines, which can be used to make more complex composites such as those designed to be used for sintering metal or other higher temperature materials. In addition, the open-source 3-D printable pelletizer chopper system can be easily expanded to even increase upon that using the STP file (STandard for the Exchange of Product). Future designs should also look into replacing the expensive and proprietary drill motor with a cheaper dc gear motor or other alternative including the distributed manufacturing of the motor itself.

5. Conclusions

This study disclosed a low-cost open-source 3-D printable invention of a pelletizer chopper for precise control of pelletizing of both single thermopolymers as well as composites for 3-D printing applications. The system was successfully developed using open-source design strategies and fabricated using low-cost open-source 3-D printers. The invention provided high tolerance thermopolymer pellets from a number of sizes capable of being used in a FGF printer as well as for recyclebot reformulation of 3-D printing filament. It has a 0.5 kg/hr throughput with one motor, and 1.0 kg/hr throughput with two motors using only 0.24 kWh/kg during the chopping process. Pellets were successfully 3-D printed directly via FGF and indirectly after being converted into high-tolerance filament in a recyclebot.

Supplementary Materials: The following are available online, Video S1: Open-source 3-D printable pelletizer chopper system during production and Video S2: Multi materials chopped simultaneously by the open-source 3-D printable pelletizer chopper system.

Author Contributions: Conceptualization, Joshua M. Pearce; Data curation, Aubrey L. Woern; Formal analysis, Aubrey L. Woern and Joshua M. Pearce; Funding acquisition, Joshua M. Pearce; Methodology, Aubrey L. Woern and Joshua M. Pearce; Writing – original draft, Joshua M. Pearce; Writing – review & editing, Aubrey L. Woern and Joshua M. Pearce.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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