CREATING AN OPEN-SOURCE, LOW-COST COMPOSITE FEEDER DESIGN TO IMPROVE FILAMENT QUALITY OF HIGH-PERFORMANCE MATERIALS TO BE USED IN FUSED FILAMENT FABRICATION (FFF)

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ABSTRACT

Composite filaments are getting increased attention in additive manufacturing (AM). More and better solutions for filament production are needed to assist researchers in discovering new materials capable of producing AM-made high-performance parts. This article presents a method for producing composite filament, including an open-source, low-cost automatic composite feeder designed to increase the accuracy and quality of the filament. The feeder includes a fibre screw designed through an iterative prototyping process to accurately control the filament's fibre percentage while reducing lumps' occurrence in a single step. An experiment evaluating the quality of filament made of Polylactic Acid (PLA) and carbon fibre (CF) tested the use of the feeder compared to manual mixing. Filament with a nominal diameter of 2.85mm with 4.5%, 7.9%, 11.2% and 14.5% CF was made. The results suggest that the composite feeder improved the filament quality. The filament diameter RMSE value was reduced from 0.08 to 0.06 and 0.15 to 0.13 for both 4.5% and 11.2%, respectively. The article concludes that the feeder design may help researchers develop and discover new materials while improving the quality of the filament.

Keywords: Additive Manufacturing, Open source design, Sustainability, Recycling, Composite materials

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1 INTRODUCTION

For advanced engineering applications of Additive Manufacturing (AM), additives like Carbon Fibre (CF) can be used to improve the mechanical properties of components (Ning et al., 2015; Parandoush and Lin, 2017; van de Werken et al., 2019). Research on the use of composite filaments has increased drastically in recent years, whereas little has been done on the topic of manufacturing composite filaments. There are available resources on compounding using thermoplastics and additives (Muralisrinivasan, 2015). However, these techniques have not been applied to filament production for AM. Also, when producing filament with additives, achieving a homogeneous material is difficult using the single-screw extrusion method (Yu et al., 2020). Commercially available filaments with well-mixed additives are available (Carolo and O'Connell, 2022). However, knowledge of the production process and material blends remain proprietary. Some online resources on compounding additives such as carbon fibres with thermoplastics to produce strong, homemade filaments exist (3Devo, 2022a; Biesterveld et al., 2021; Ning et al., 2015), but the current amount of research is limited. Accordingly, this article aims to contribute relevant knowledge for researchers and the maker community. It is evident that making open-source additive manufacturing research designs (Birkeld et al., 2022; Johnson et al., 2011; Pearce, 2012) can democratize and boost knowledge in the field. Therefore, this paper investigates composite mixing for filament production as a low-cost, open-source mixer for filament extrusion machines is presented and evaluated.

Mixing additives in plastic extrusion may fail in several ways (Giles Jr et al., 2004). First, different-sized objects tend to separate based on size and weight (D18 Committee, 2010). E.g., a box with Lego where the smallest items fall through the matrix of large objects and end up at the bottom. This sifting segregation, or «Lego effect», occurs in the hopper; while the extrusion screw is churning, the fibres fall to the bottom, increasing the fibre concentration in some areas of the filament and decreasing concentration in others. A good distributed and dispersed mix may also be challenging when mixing with a single screw (Gale, 1997; Yu et al., 2020) due to small particles self-aggregating together (Heidemeyer and Pfeiffer, 2002; Muralisrinivasan, 2015). Some ways to overcome this issue are using fibre pellets, blending the composite materials together (Ning et al., 2015), or introducing small batches of material in order to achieve higher control. The latter method will be investigated in this article.

2 METHOD

The following section describes how a composite filament was produced in this study, along with an experiment setup to evaluate the filament quality. An automatic low-cost open-source composite feeder system controlling the fibre and polymer composition of the filament is also described.

Method overview

The composition of the filament created for this article consisted of PLA (NatureWorks LLC, 2020) and 80µm unsized carbon fibres (SGL Carbon, 2021). The overall process can be seen in Figure 1.

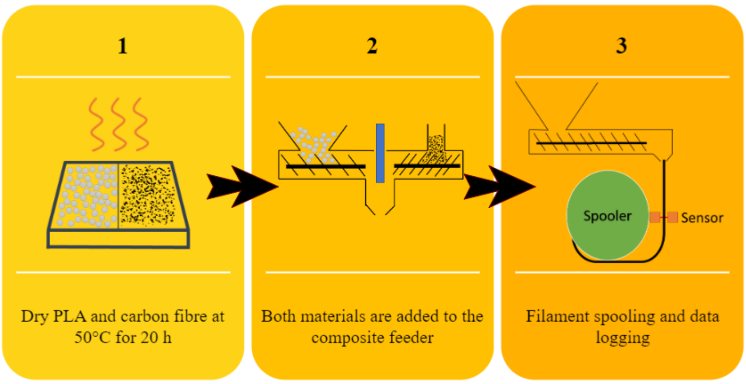

Figure 1. 1) PLA and carbon fibres are dried at 50°C for 20 hours. 2) PLA and fibres are added to the feeder. 3) Filament is produced using the filament maker

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First, PLA and carbon fibres are dried for 20 hours at 50°C to remove moisture. Both materials are then fed into the automatic composite feeder. The composite feeder mixes the two materials at predetermined weights and pushes the mixture into the filament maker, similar to previous concepts of starve feeding (Parandoush and Lin, 2017). The filament is then manufactured according to the instructions on the filament extruder. The filament extruder used for this article is the 3Devo Composer 450 (3Devo, 2022a); however, the composite feeder design applies to any generic filament extrusion machine, e.g., RepRapable Recyclebot (Woern et al., 2018). In addition, the filament's dimensions are logged through a built-in sensor before spooling.

Composite feeder design

To achieve high accuracy of both material composition and dimensional filament quality, a low-cost open-source automatic composite feeder—referred to as "Feedo"—was built. Feedo's task is to give a generic filament extruder the capability of extruding fibre-reinforced thermoplastic filament with a higher degree of homogeneity than what is possible with pre-mixing plastic and fibre by hand. The entire setup, i.e., Feedo and its interaction with the filament maker, can be seen in Figure 2.

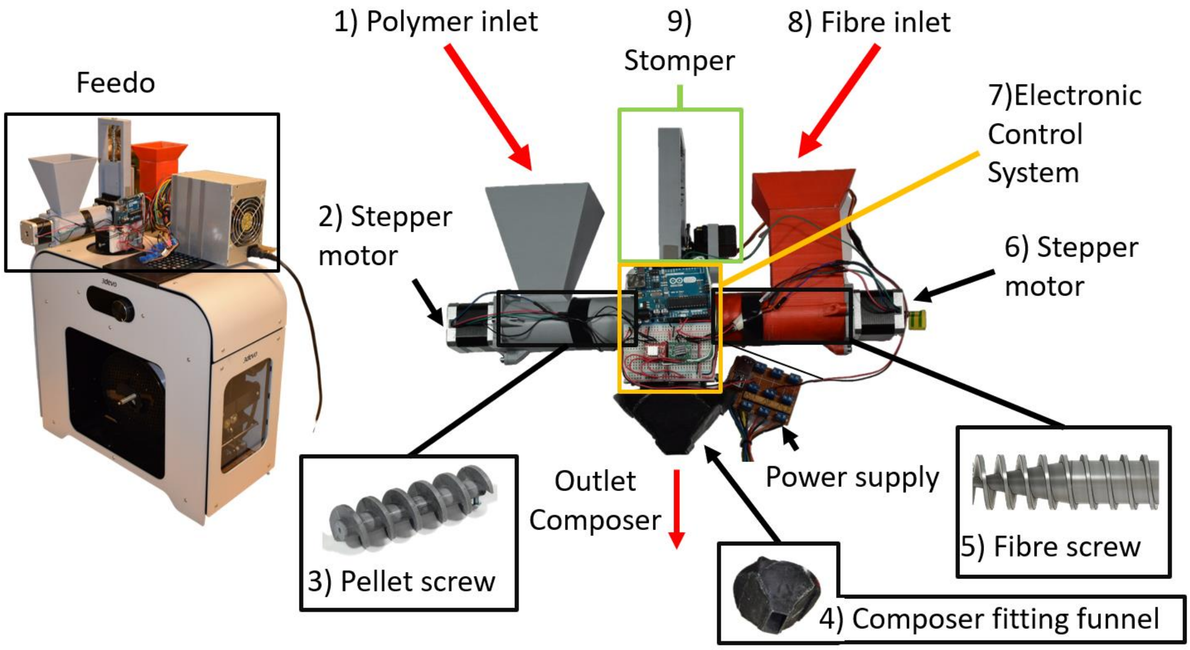

Figure 2. 1) Polymer inlet. 2) Plastic screw stepper motor. 3) Pellet screw. 4) Composer fitting funnel. 5) Fibre screw. 6) Fibre screw stepper motor. 7) Electronic control system. 8) Fibre inlet. 9) Stomper

The polymer inlet (1) is designed as a generic funnel to refill pellets easily. The fibre inlet (8) was designed with a straight section to avoid ratholing (Polizzi et al., 2016). The two different Archimedes screws (3 and 5), used to extrude precise masses of pellets and fibre, are driven by the two NEMA17 stepper motors (2 and 6). The electronic control system (7) comprises two a4988 stepper drivers, an Arduino UNO, and a power supply with 5V and 12V outputs.

After materials from both barrels have been pushed into the joint funnel (4), the stomper (9) becomes operational. A stomper is added in Feedo's centre to press the material into the extruder screw due to the low weight of the material itself. Without sufficient pressure on the material, the composite mixture will "float" on top of the extruder screw. The stomper is a rectangular bar pushed down by a spring connected to a rack. A DSS-M15 servo motor, regulated by the control system, lifts and lowers the stomper every 30 seconds to provide space for new material extruded into the funnel. The composer fitting funnel (4) connects Feedo to the filament maker, ensuring that no material escapes. The fibre screw (5) consists of a straight section covering the size of the fibre inlet, followed by a tapered section (Figure 3).

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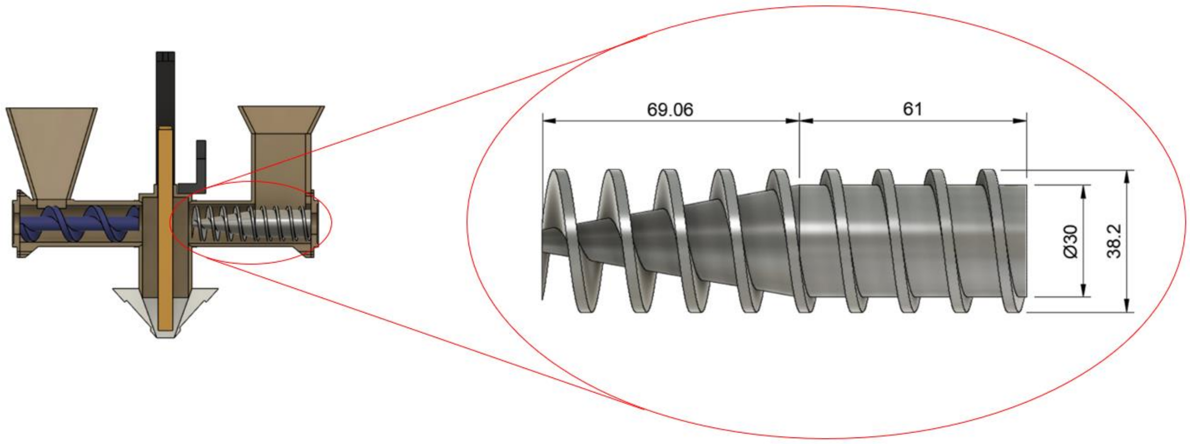

Figure 3: Fibre screw design

After the hopper section of the screw, the fibre is measured out and moved forward in the screw. Dried carbon fibre tends to have a higher viscosity than undried fibre, clogging previous designs where the entire inner diameter of the screw is constant. This issue was solved through rapid prototyping of several screw designs, resulting in a screw with a constant volume under the fibre inlet for maximum control of the amount of fibre it takes up and a tapered section to give the fibres space to expand. The tapered design of the screw provides room for the carbon fibres to move such that the screw does not clog. A polished steel pipe surrounds the fibre screw to reduce friction between the fibre and the barrel, and the screws are spray painted to improve the surface finish.

Experiment setup

In order to evaluate the accuracy of the fibre-polymer ratio produced with Feedo, an experiment was conducted to test the carbon fibre and polymer weights per screw revolution. This calibration was done by placing Feedo over a JS-100xV scale (JS-100xV, Midlands scales, Kingswinford, England) with 0.01g accuracy and extruding various masses onto the weight. First, the material weight resulting from one revolution of the plastic screw was measured and noted as a baseline for the mix ratio. Measurements of the fibre weight were then recorded 27 times each for 1, 2, 3 and 4 screw revolutions. Average weights and standard deviations were then calculated based on these measurements.
An experiment was also designed to test the quality of the filament produced by automatic mixing compared to that made by manual mixing. A detailed overview of the production process for both cases is presented in Figure 4.

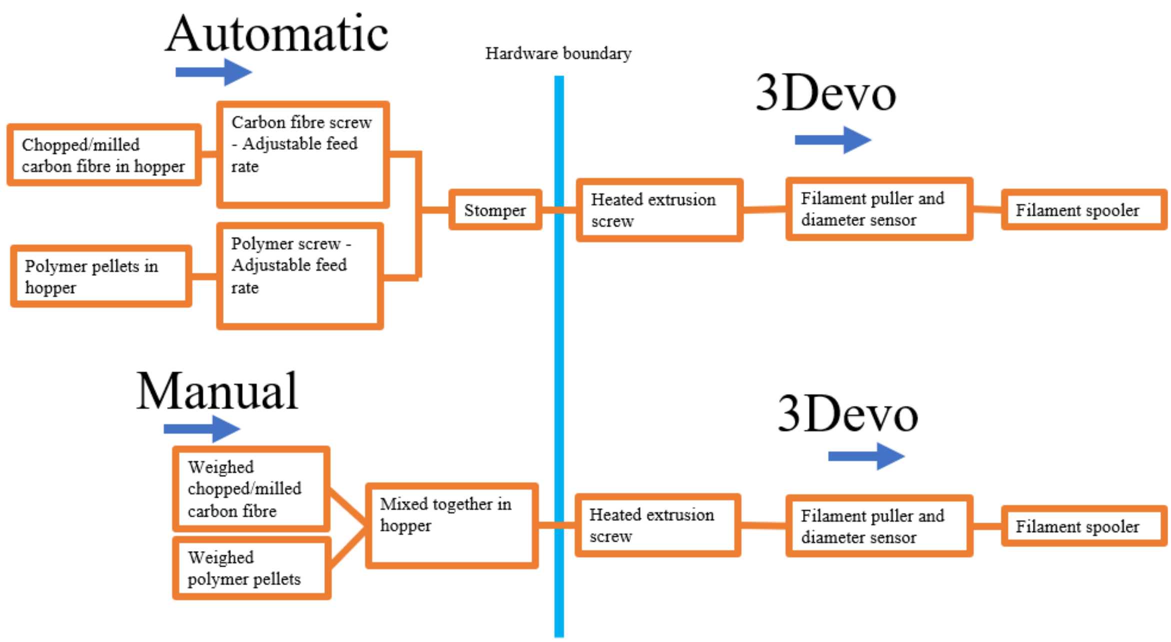

Figure 4. A flowchart describing both the automatic and manual filament extrusion process

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After the bag with carbon fibres was opened the first time, the fibres were pre-dried at 200°C for 30 minutes. Before an extrusion session, fibre and PLA were dried for 20 hours at 50°C to reduce lumps in the final filament (Giles Jr et al., 2004). Drying was done because several preliminary tests suggested that lower moisture content resulted in a smoother filament, in line with guidelines for thermoplastic extrusion (Neboian, 2022).
The automatic process started by placing the dried materials in their respective hoppers. Room conditions were 23°C and humidity was 25%. Feedo then extruded the PLA-CF mix into the hopper of the filament maker. After preparing the filament maker for extrusion—including verifying filament extruded at 2.85mm±0.05mm in the 3Devo software, DevoVision (3Devo, 2022b)—spooling and logging were started. Four rolls of filament were made for 1, 2, 3 and 4 revolutions of the fibre screw per 1 revolution of the plastic screw, corresponding to 4.5, 7.9, 11.2 and 14.5w_{CF}% (carbon fibre weight percentage), respectively. The dimensional accuracy of the filament was recorded by the built-in sensor on the filament maker and logged into DevoVision (3Devo, 2022a).
The manual process was similar to the automatic process, but instead of letting Feedo mix the two materials, they were mixed manually with equal weights in a cup and added to the hopper, according to 3Devo's guide on mixing additives (3Devo, 2022a). Both processes were monitored to ensure no external or internal factors affected the experiment in any harmful way, e.g., a tool similar to Feedo's stomper was used to ensure correct feeding and back-pressure inside Composer. Logging of dimensional accuracy of manual mixing was done at 4.5 and 11.2w_{CF}%.

3 RESULTS

The following section presents the results on the accuracy of mass flow the fibre screw and pellet screw were able to produce, i.e., calibration of the machine and filament quality gathered from manual and automatic extrusion tests. The first part will cover the calibration results, and the second will show the variation of filament dimensions over time. The third part will show statistical values calculated from the filament dimensions, and the final part will show images of the different extruded filaments on spools.

Calibration results

The mass flow and accuracy of the two materials based on screw revolutions are presented in Table 1. The carbon fibre weights per screw revolution are highlighted in Figure 5.

Table 1. Mass flow and accuracy based on screw revolutions

Screw type	Revolutions	Avg. weight [g]	SD [g]	SD [%]	w_{CF}%
Pellet screw	1	20.81	0.47	2.3	-
Fibre screw	1	0.98	0.06	5.8	4.5
Fibre screw	2	1.79	0.13	7.3	7.9
Fibre screw	3	2.61	0.14	5.4	11.2
Fibre screw	4	3.53	0.07	2.1	14.5

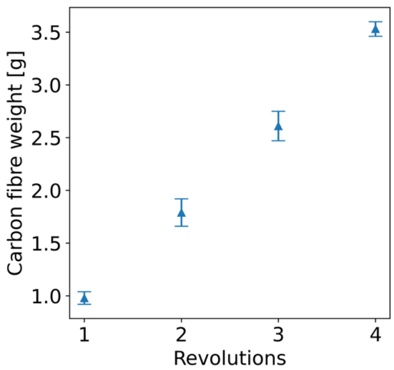

Figure 5. Carbon fibre weight as a result of fibre screw revolutions

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The weight percentage of carbon fibre in the mix (w_{CF}%) is calculated with one polymer screw extrusion of 20.81g as the baseline amount of PLA used in our experiment. Figure 5 shows an increased carbon fibre weight standard deviation for 2 and 3 revolutions compared to 1 and 4 revolutions. I.e., 0.13g and 0.14g as opposed to 0.06g and 0.07g, respectively.

Filament quality results

Figure 6 shows the filament diameter logged through DevoVision from the six different filaments (A to F) from spooling start up to 500 seconds into the spooling. A-D shows extrusion data from the automatic process, and E-F shows manual feeding. Figure 6 also highlights outliers from each graph in A1 to F1.

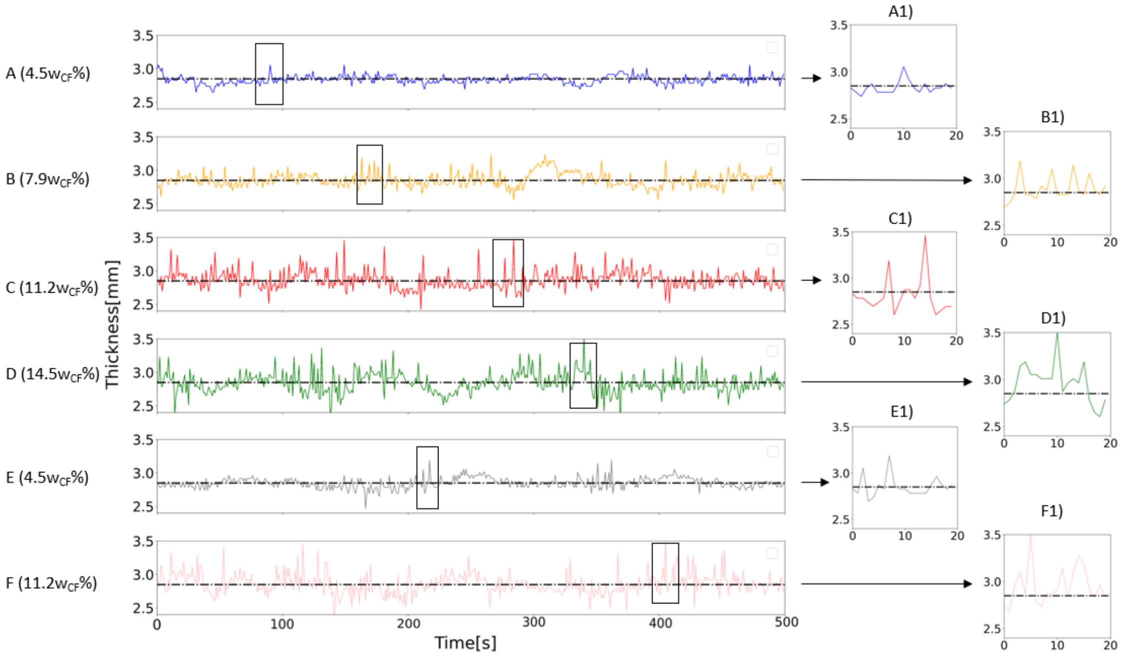

Figure 6: Graph depicting the filament diameter measured during the experiment for all cases. A) Feedo 4.5w_{CF}%. B) Feedo 7.9 w_{CF}%. C) Feedo 11.2w_{CF}%. D) Feedo 14.5w_{CF}%. E) Manual 4.5w_{CF}%. F) Manual 11.2w_{CF}%. A1) [80s-100s]. B1) [160s-180s]. C1) [270s-290s]. D1) [330s-350s]. E1) [210s-230s]. F1) [400s-420s]

One highly notable characteristic of the data in Figure 6 is an increase in diameter variation according to the increase of carbon fibre content. This increase is visible by comparing plots A with D and E with F. The best-performing filament arose from the automatic feeding process with 4.5w_{CF}%, visible by its low number of spikes in plot A. The spike in A1 is also notably smaller than in E1.
Table 2 shows the different numerical values from each carbon fibre content with manual and automatic feeding. Figure 7 shows the RMSE, calculated from the graph values depicted in Figure 6, and the change in diameter (ΔD), calculated from Max D and Min D, for each w_{CF}% in both the automatic and manual filament production processes.

Table 2. Statistical values from automatic and manual extrusion

Feeding method	**Automatic extrusion**				**Manual extrusion**	
Graph (Figure 6)	**A**	**B**	**C**	**D**	**E**	**F**
w_{CF}%	4.5	7.9	11.2	14.5	4.5	11.2
RMSE	0.06	0.10	0.13	0.16	0.08	0.15
Max D [mm]	3.053	3.232	3.457	3.502	3.187	3.502
Min D [mm]	2.649	2.559	2.424	2.110	2.469	2.334
ΔD [mm]	0.404	0.673	1.033	1.392	0.718	1.168

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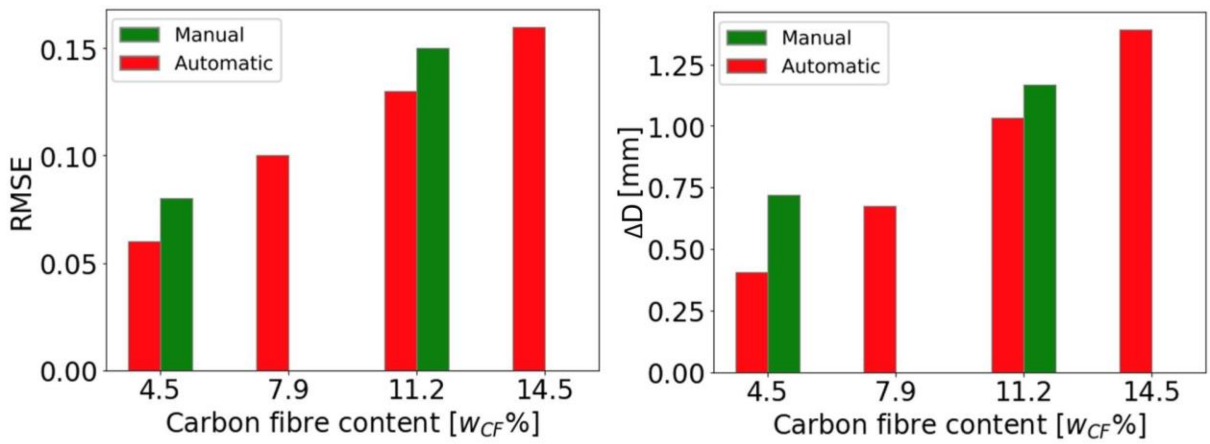

Figure 7. RMSE and ΔD values for each w_{CF}% in both automatic and manual filament production process

Comparing automatic to manual feeding, the RMSE increases from 0.06 to 0.08 and 0.13 to 0.15 for 4.5w_{CF}% (A and E) and 11.2w_{CF}% (C and F), respectively. This increase in RMSE corresponds to the ΔD values increasing from 0.404mm to 0.718mm and from 1.033mm to 1.168mm for 4.5w_{CF}% and 11.2w_{CF}%, respectively. The same feature can be seen by comparing the red to the corresponding green columns in Figure 7.

Looking at Table 2, one can see that the ΔD of the filament containing the lowest concentration of carbon fibre (A) is 0.404mm, and for the filament with the highest concentration (D) is 1.392mm, i.e., an increase of 0.988mm. This increase is better visualized by comparing the lowest to the highest red columns in Figure 7. The maximum values from Table 2 is also seen in graphs A1 to F1 in Figure 6. Figure 8 depicts the different filaments spooled in the experiments for a qualitative assessment of how the filament looks and how lumping worsens with increased carbon fibre content.

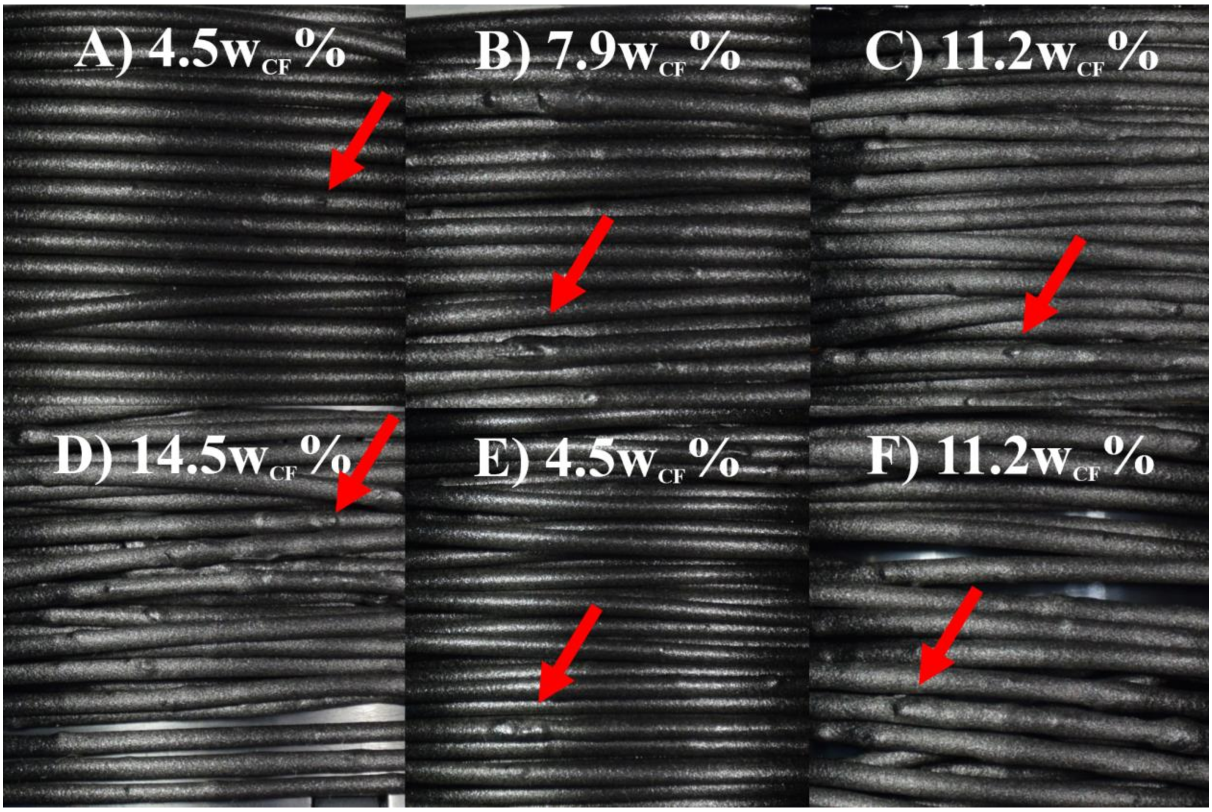

Figure 8. Images showing the quality of the produced filament for all cases. Arrow indicates where there are examples of lumps. A) Automatic 4.5w_{CF}%. B) Automatic 7.9 w_{CF}%. C) Automatic 11.2w_{CF}%. D) Automatic 14.5w_{CF}%. E) Manual 4.5w_{CF}%. F) Manual 11.2w_{CF}%.

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Filaments from A to D, i.e., the ones from the automatic production, show a considerable increase of visible lumps in size and frequency when w_{CF}% is increased. Comparing A and E, containing the same carbon fibre content but using different feeding methods, one can see a slight increase in lump size in E. The same can be found when comparing C and F.

4 DISCUSSION

The data from the DevoVision software shows a consistent trend that when carbon fibre content increases, the diameter variation, max diameter and RMSE (Table 2) of the filament get worse. Comparing the similar w_{CF}% from the two feeding methods, the RMSE, outlier graphs (Figure 6) and ΔD (Table 2) all show that the manual feeding performed worse than automatic for both 4.5w_{CF}% and 11.2w_{CF}%. The trend is also visible in the final extruded filament (Figure 8), with the actual lumps mirroring the graphs, RMSE and ΔD. This difference is substantiated by the bars in Figure 7. The results indicate that using the automatic feeder will increase the performance of all parameters discussed.

The calibration of Feedo shows a linear trend in Figure 5 of fibre mass flow with increased revolutions, meaning we can efficiently predict and control fibre and pellet mass feeding. The calibration results are also consistent as each extrusion of ~21g results in extrusion for ~200s with a length of ~2.8m of filament.

Preliminary testing showed that drying the fibre reduced visible lumps substantially. Thus, starting with completely dry fibre for the experiment was necessary. The number of lumps in the filament still increased however, with high carbon fibre content, possibly arising from several issues. First, there may still be some moisture left in the fibre; i.e., an increased fibre amount yields an increase in moisture, which may be related to increased porosity at higher fibre concentrations (Ning et al., 2015). Second, sub-optimal distributive mixing can still happen inside the filament maker, despite the increased performance provided by the automatic feeding system, and as the carbon fibre level increases, the frequency and size of undistributed carbon fibre might increase accordingly. Third, introducing carbon fibres in thermoplastics will alter the thermal properties of the filament. Unmelted particles result in lumps (3Devo, 2022a); therefore, increasing the fibre level may increase the thermal energy needed to melt the composite mixture, thus increasing viscosity. Increasing the temperature or reducing the rotational speed of the filament maker may help overcome this issue and may reduce lumps (Mount III and Chung, 1978). Fourth, nozzle build-up can lead to uneven filament and is dependent on nozzle temperature (3Devo, 2022a). Nozzle build-up was, however, not observed.

It is possible to minimize the lumps with increased carbon fibre content by adjusting the extruding parameters of the filament maker in between filament rolls. However, changing experiment setup parameters was avoided in order to get consistent data for the different feeding methods, including consistent process parameters for Composer for both the manual and the automatic extrusion process. Feedo is designed for a generic extrusion machine, and the scope of the experiment was to use a low-cost open-source research tool to increase filament quality compared to manual mixing and general pre-mixing.

Design improvements

In the Feedo-design, there are other ongoing developments and lessons learned. First, enhanced carbon fibre control can be achieved by preventing fibre from slipping between the screw and barrel and removing clogging problems due to high friction. Tighter tolerances between the barrel and screws and lower friction for the fibre rubbing against the screws can be achieved with machined screws with a good surface finish. Clogging of the fibre barrel may also be solved by increasing the screw torque by adding a small planetary gearbox or upgrading the stepper motor. Another solution to the clogging problem could be to slightly increase the pitch in the tapered section of the screw to provide some additional room for the carbon fibres to move.

Even though no changes to the filament maker were made, general extruder design improvements have been considered. The single-screw design of the 3Devo Composer offers limited mixing of the material; a small mixing zone does the only intentional mixing that occurs in the barrel at the end of the extruder screw. A solution to this would be to implement a twin screw design like the one suggested by Yu et al., (2020). The filament diameter data retrieved from DevoVision was recorded at 1Hz with an accuracy of 43µm (3Devo, 2022a). The filament in the experiment was extruded at

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approximately 14mm/s. The sensor frequency might have been one of the main contributors to errors in the experiment since 1Hz is too low sampling rate to capture all diameter deviations. The extrusion data was therefore recorded for 500 seconds to capture more of the filament's lumps, arguably long enough for comparing the filaments. The sensor frequency could be altered for future experimentation, but the scope of this paper was to make a low-cost add-on to a generic extruder and investigate the resulting filament. Changes in the Composer software were therefore not made.
This paper uses PLA as thermoplastic because it is a low-cost material for prototyping and optimizing the process. Further research in custom-made composite filament should, however, continue with high-performance materials such as PEEK and Nylon reinforced with carbon fibres of different lengths. Increasing the carbon fibre length may increase material properties in FFF (Ning et al., 2015). Filaments with long fibres are hard to obtain commercially, as the fibre length often wary between 80µm and 300µm due to compatibility with standard nozzle sizes. By creating their own filament, researchers may be able to develop and test new materials for high-performance AM parts (Bjørken et al., 2022). Fibre length beyond 1mm has proven to enhance the strength of injection moulded components (Botelho et al., 2003; Calignano et al., 2020) and could be compatible with AM by increasing nozzle size. The research into fibre length in AM is limited, and it is challenging to map existing filaments due to producers' unwillingness to disclose the specific fibre length they use. The authors hope this paper will contribute to increased research in this area.

5 CONCLUSION

Given the RMSE- and ΔD-results on filament quality, this article suggests that the use of Feedo will increase accuracy in composite filament production. These results may help future researchers develop and discover composite materials better suited for additive manufacturing of high-performance applications by making the filament production process easier. Also, since the composite feeder presented in this article is both open-source, low-cost and made by 3D printed parts and easily accessible electronic components, implementing the design for other filament makers can easily be done.

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