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A Material-Recycling Unit for the Fused Deposition Modelling of Three-Dimensional Printing Systems

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Abstract: Fused deposition modelling (FDM) three-dimensional (3D) printing technology is one of the most common additive manufacturing (AM) technologies due to the relatively low cost of the printing units and materials. Although cost-effective, this technology is not conceived to convert 100% of the raw material into a complete product, creating a potential plastic waste problem. To recycle the plastic waste from the FDM machine into reusable filaments, the concept of a 3D printer material-recycling machine (3DP-MRM) was developed using CREO Parametric 9.0 software. A prototype with four systems, including a spooler system, extruder system, display system, and filament-positioning system, was manufactured in-house with complete run experiments. The tests of the 3DP-MRM were applied, and the machine worked successfully among all the designed functions with minor issues.

Keywords: recycling; fused deposition modelling; 3D printing; additive manufacturing

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Citation: Nattukallingal, M.N.; Ran, Z.; Abass, A. A Material-Recycling Unit for the Fused Deposition Modelling of Three-Dimensional Printing Systems. *Appl. Sci.* **2023**, *13*, 7515. https://doi.org/10.3390/app13137515

Academic Editor: Guijun Bi

Received: 27 April 2023
Revised: 14 June 2023
Accepted: 23 June 2023
Published: 26 June 2023

1. Introduction

Fused deposition modelling (FDM) is a melt extrusion process that exhibits the ability to fabricate intricate geometries through the deposition of molten materials in the form of a filament [1,2]. It has gained substantial recognition as the pre-eminent commercially viable technique for three-dimensional (3D) printing [1,3]. The 3D-printed structure is created using a layer-by-layer approach, where the print head assembly is moved over a platform to extrude the molten filament tip in precalculated positions [3]. Materials such as Acrylonitrile Butadiene Styrene (ABS), Polylactide (PLA), Thermoplastic Polyurethane (TPU), etc., are commonly used in FDM manufacturing [1,4].

Products of FDM are increasingly present in many biomedical [5–9], tooling [10–13], electronic [14], automobile, and aerospace applications [15–17], etc., playing increasing roles in the industry [14]. However, at the same time, the continued build-up of plastic waste in landfills has become a significant concern for environmental sustainability [18]. Ideally, FDM technology should exclusively employ materials that are essential for the final product. However, this is not feasible due to the need for support structures in various geometries and the frequent need to reprint defective objects, especially during prototyping [16]. To tackle the issue of plastic waste in FDM, several studies have explored the generation of support materials, focusing on modifying the material behaviour or optimising the support structure without recycling [19–21]. Still, this option is highly restricted by the geometry of the 3D-printed object. Recycling plastic waste, especially post-consumer, is a different method [22]. On a global scale, plastic recovery and recycling rates tend to be lower compared to other commonly utilised materials, such as paper, glass, and metals, even in countries with advanced waste management systems and extensive recycling expertise [23–25]. This relatively low recycling rate can be attributed, in part, to the diverse range of plastics, additives, and composites used in various applications [23]. In the realm of plastic recycling methods, while there have been advancements in chemical recycling, mechanical recycling remains the predominant technology used for recovering plastic waste, which involves the employment of mechanical processes to transform the plastic waste into new plastic products [26–29], which is a highly effective method of plastic recycling based on time, economic cost, and environmental impact [30]. Typically, the recycling of plastic mechanically involves melt blending, sorting, shredding, and reprocessing [23,30].

The existing plastic-recycling machines are expensive and occupy a large amount of space. Their design target is to recycle wide-ranging plastic waste, not limited to FDM waste, into 3D printer filaments or make filaments [31,32]. A comprehensive machine or machine attachment unit explicitly designed for the recycling of waste from 3D printers is not widely available on the market and is typically associated with high costs. The Filabot company (Barre, VT, USA) offers an all-in-one configuration for 3D-recycling setups, which includes a reclaimer, extruder, airpath, spooler, and pelletiser. This setup is available at a price of approximately GBP 1500 and requires a large setup volume [33]. The ProtoCycler+ Filament Maker and Recycler introduced by ReDecTec (Toronto, ON, Canada) is an all-in-one extruder machine with a built-in manual material shredder, mainly focusing on research purposes and is estimated to be an expensive unit [34]. Similar products were commercialised by Precious Plastic but require a large amount of setup space and are more suitable for the manufacturing end of recycling process [35]. In short, the commercially available FDM-waste-recycling machines are generally either expensive or do not have all-in-one configurations.

The current prototype creation study aimed to design, manufacture, and test a prototype of a desktop-sized material-recycling unit for FDM-3D-printing systems at a low cost. The 3D printer material-recycling machine developed in this study will be referred to as (3DP-MRM) in the rest of this manuscript. The 3DP-MRM reuses the thermoplastic materials used in the FDM additive manufacturing process and allows them to be recycled into ready-for-use filaments.

2. Materials and Methods

The design process of the 3DP-MRM is based on the Product Design Specification (PDS) method [36], which includes the full details of the design requirements. The process started with the parameterised goal settings through the creation of a PDS and the lateral monitoring of progress under each goal, as shown in Table 1.

Table 1. PDS table of the designed and developed filament-recycling machine.

Category	Details	Design Intention
Performance	Material available	PLA and ABS.
	Input material type	Plastic waste and industrial pellets.
	Heating time (to 200 °C)	Under 10 min.
	Included options	Extruder, mixer, automatic spooler, and filament positioner to avoid a tangled filament spool.
	Heating element	Heating band.
	Temperature	The maximum nozzle temperature is 300 °C.
	Filament thickness	1.75 mm.
	Tolerance	±0.06 mm.
	Cooling system	Forced fan cooling.
	Extruder	Forced extrusion using a compression screw.
	Sensors	Filament thickness, nozzle temperature, filament continuity sensor, motor speed controller.
	Extrusion speed	300 g/h.

Table 1. *Cont.*

Category	Details	Design Intention
	Continuous operation	A 4 h maximum production of 1200 g of filament.
	Supply voltage	Internal 220 V A.C. power supply with built-in electrical fuse
	Noise and vibration	Must be able to operate in an office or lab environment with minimum noise and vibration.
Size and weight	Weight	Under 8 kg.
	Dimensions	Maximum of 420 mm × 370 mm × 240 mm. To be usable in a desktop environment.
Cost	Product cost	GBP 250.
Aesthetics	Chassis	Separate high-strength chassis to support all the major components.
	Body	Semi-box design with all major components designed to be inside the cover panels. Aesthetically pleasing, to be used in a desktop or lab environment.
Manufacturing	Material	ABS, aluminium, and steel.
	Method	FDM printing, laser cutting, lathe turning.
Ergonomics	User interface	Easy to operate without complicated settings to choose from.
	User training	No user training is required to operate the machine.
Safety	Safety guards	All the sharp moving components, hot surfaces, and high-current wires must be secured and out of reach during regular operation.
	Heat protection	Heat protection tapes, heat protection guards, overheat shutoff, overheat warnings, heat protection padding around hot components, and ceramic separators to protect all components from hot parts.
	Electrical Fuse	Electrically fused.
Transportation	Shipping	Minimum-sized and difficult-to-break components to minimise damage during shipping. Must be able to be shipped by land, air, and sea.
	Packaging	All the components are packaged and secured. The total volume and weight of the packaging must be low to be able to be shipped internationally by air or sea in an economical manner.
Environment	Working condition	To be used in a desktop or small-space environment.

The 3DP-MRM was developed into four major systems based on their functions: the spooler system, extruder system, display system (control unit), and filament-positioning system. All these systems consist of multiple components considered as different sub-assemblies. Before being manufactured and tested, the concept model was designed using CREO Parametric 9.0 software (Parametric Technology Corporation, Boston, MA, USA).

2.1. Spooler System

The spooler system is the collector of the recycled filament, which pulls and rolls the filament onto the replaceable spool. A 12 V 30 RPM D.C. motor with a gearbox is used to rotate the replaceable spool depending on the rate of material extrusion from the extruder system. A motor controller controls the speed of the motor. Figure 1 shows the fully assembled spooler system with all the components. Two different locking mechanisms are used to secure the replaceable spool to the spooler shaft, of which one mechanism locks the shaft in place but allows for free rotation on the shaft axis. The spool can be removed from the shaft and replaced with a new one when required. The motor and the shaft can be twisted around the motor's vertical axis in a predetermined path, as seen in Figure 1B, where the blue circle indicates the spool's location and its movement path when it rotates. Most of the components were 3D-printed with ABS material, and the other components of the spooler system were made from stainless steel and aluminium.

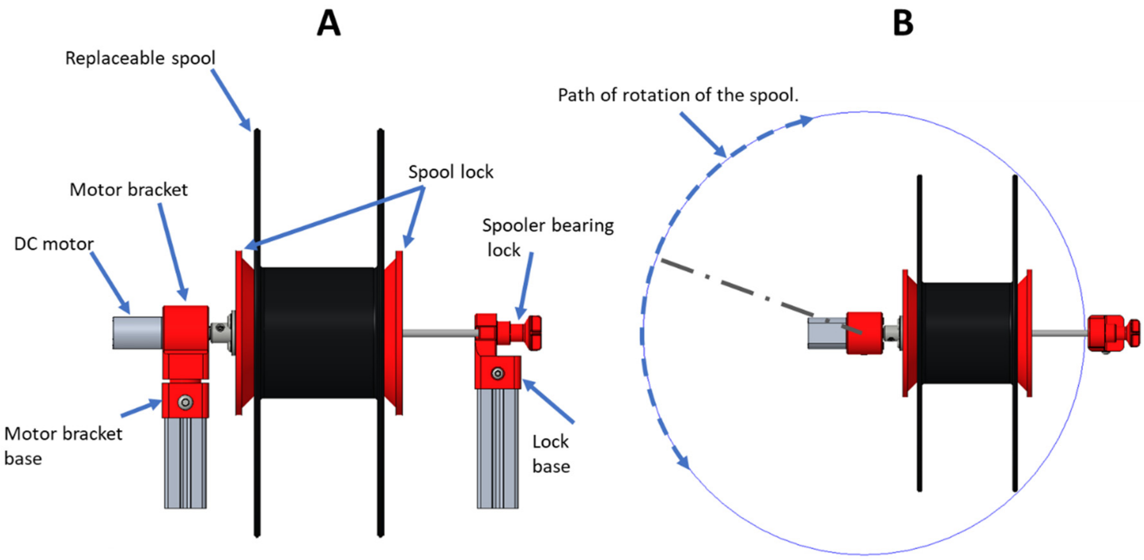


Figure 1. (**A**) Sub-assembly of the spooler system (front view). (**B**) Top view with a blue circle showing the clearance for the spool when turning around the motor axis.

A spooler-bearing lock in this system was designed to avoid using the supports in which overhangs were present, as shown in Figure 2. All 90° overhangs were avoided in the design, and 30° to 50° overhangs were used to enable 3D printing without supports (see Figure 2B). A cross-sectional view of the fully assembled part is shown in Figure 2C, where the second piece is moved up to make space for the ball bearing. The ball bearing reduces the friction created by the rotating spooler shaft on the spooler-bearing lock. Although the design of the spooler-bearing lock has two individual plastic parts, it was designed for printing as a single part by creating a 0.5 mm gap between the walls to enable movement.

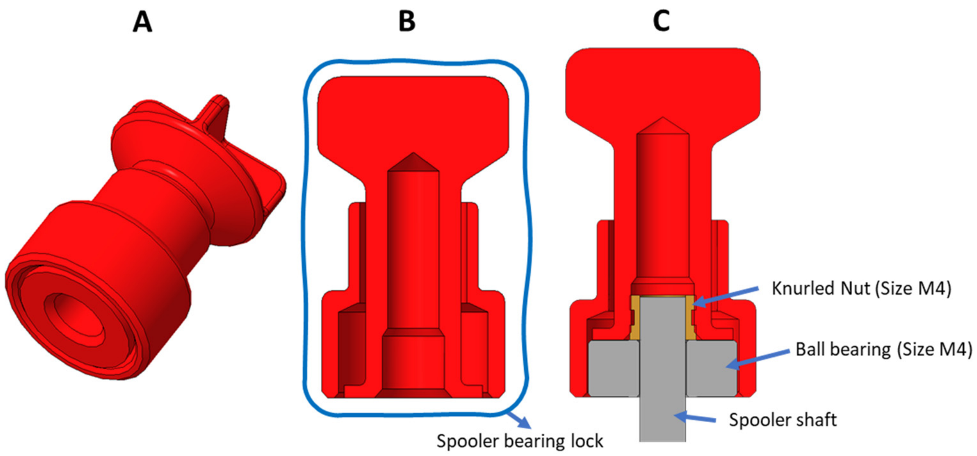


Figure 2. Single-piece design created for 3D printing. (**A**) Model ready for 3D printing. (**B**) Cross-sectional view of the model with no 90° roofs/overhangs. (**C**) fully assembled model.

2.2. Extruder System

The machine's most important part is the extruder system, which extrudes plastic chips into thin filaments for 3D printing. As seen in Figure 3, the extruder system consists of an extruder motor, chip collector, heating band, and auger bit inside the barrel. The auger bit acts as the compression screw, pushing and mixing the molten plastic through the barrel. The extruder motor is a high-torque 12 V 20 RPM DC motor with a gearbox built into it. A temperature sensor is placed on top of the barrel of the extruder to avoid safety issues from the extruder temperature and extruder overheating. A Teflon spacer is added between the hot barrel and extruder support brackets to create space, isolating the heat. The 3D printing method with ABS material was applied to the parts, the Teflon spacer was made from a 1 mm Polytetrafluoroethylene (PTFE) sheet, and the rest were mainly made from stainless steel.

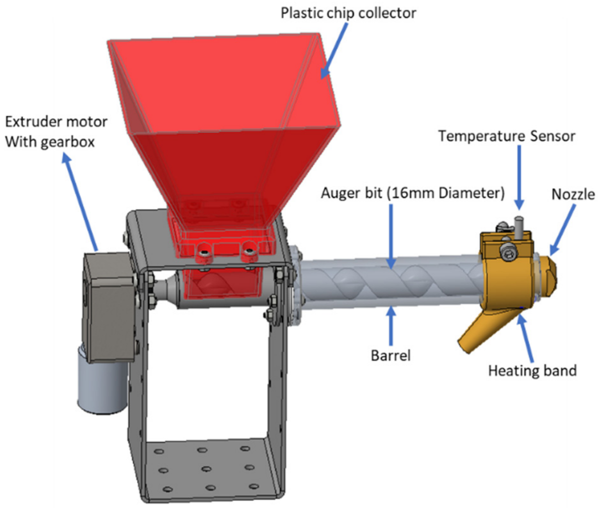


Figure 3. Sub-assembly of extruder system with transparency mode turned on for the barrel to show the auger bit.

The chip collector in the system was designed for printing without a support material. Another part utilises an angled roof design to avoid using support structures, as shown in Figure 4. This model has a support structure inside the rectangular hole, which increases the possibility of the support structure fusing with the walls.

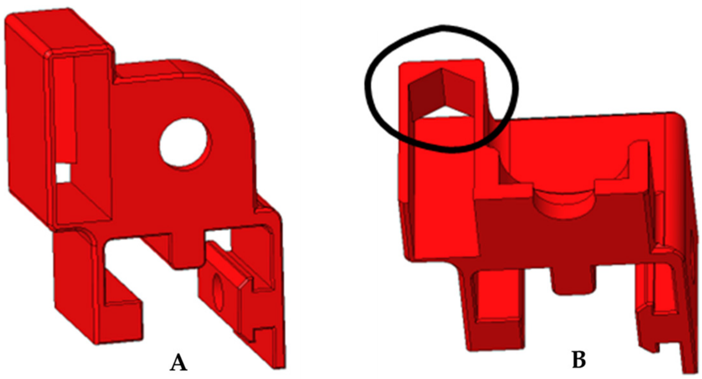


Figure 4. (**A**) Part front, which is placed on the build plate. (**B**) Chamfered overhang/roof (circled) to enable printing without supports in tight spaces.

2.3. Display and Control System

The display and control system worked as the brain of the machine. Figure 5 shows the components packed inside the case, including the Arduino Mega open-source electronic board, display, two motor controls, main power switch, fuse holder, and heating band solid-state relay. The components are closely packed to allow air to flow through the interior. The outer display case was designed to eliminate the supporting materials' use using round corners instead of sharp corners, as shown in Figure 6. The structure and support of this system are mainly ABS for 3D printing.

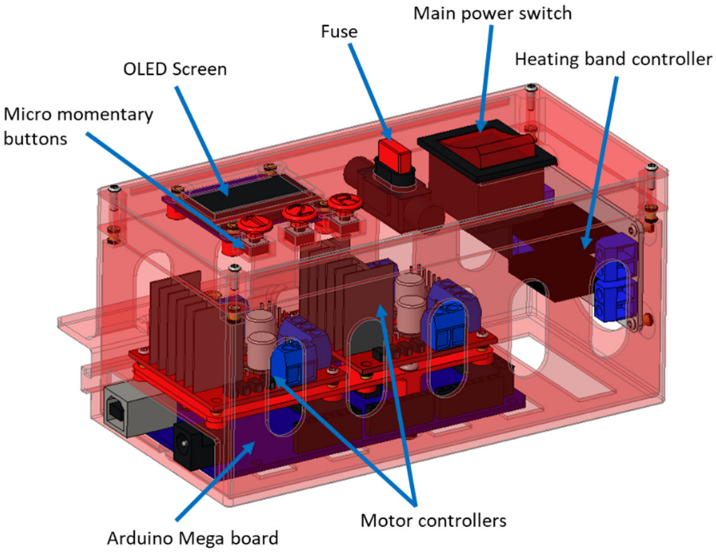


Figure 5. Sub-assembly of control and display system.

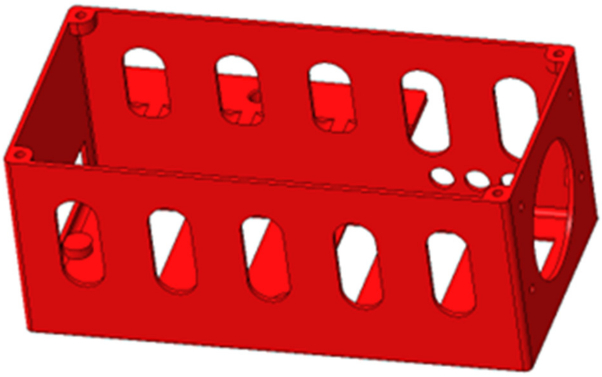


Figure 6. Outer displayed case with circular cut-outs.

2.4. Filament-Positioning System

The filament-positioning system correctly positions the newly made filament by moving the filament break detector in the middle, as seen in Figure 7. The filament is inserted through the white PTFE tube and connected to the spool of the spooler system. A 12 V D.C. motor, through a gearbox, drives the M4 threaded shaft connected filament break detector. In addition to the PTFE tube, the filament position system was mainly ABS with 3D printing.

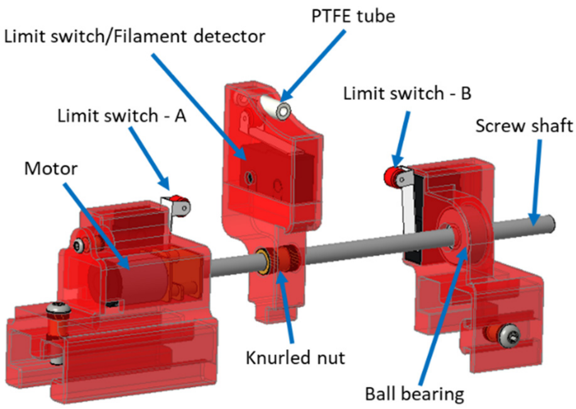
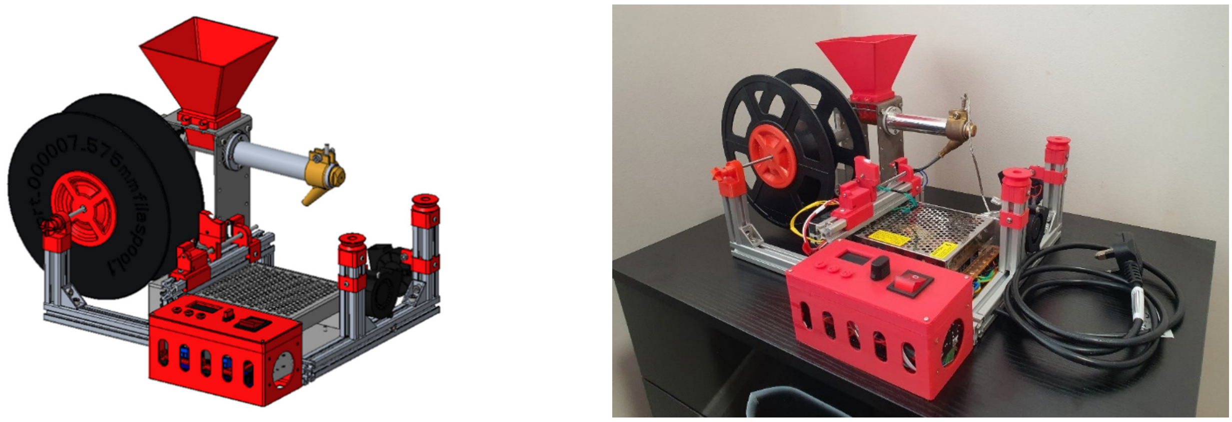


Figure 7. Sub-assembly of the filament-positioning system with transparency mode turned on for outer casing to show the internal components.

2.5. Prototype and Validation Experiment

When the individual system's development was finished, the four sub-assemblies formed the final concept assembly with the cooling fan, power supply, bare chassis, etc. As shown in the final concept in Figure 8A, the parts were either 3D-printed or made in-house; all others were combined to assemble the final prototype, as shown in Figure 9.



(A) (B)

Figure 8. (**A**) Final concept assembly. (**B**) The prototype of the 3D printer filament-recycling machine.

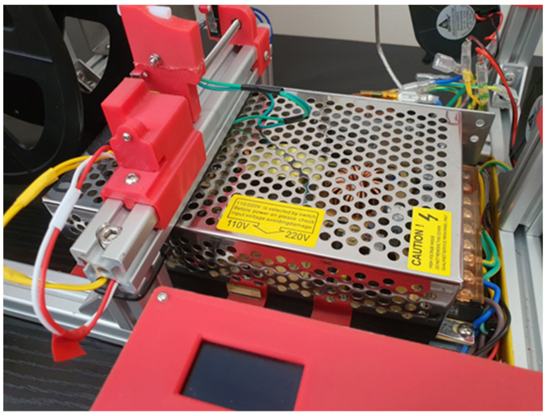


Figure 9. 12 V 20 A power supply used for the machine.

The validation experiment used around 0.5 kg of FDM PLA waste material that was crushed to a size enabling it to be fed to the hopper. The machine was switched on in a well-ventilated room equipped with a smoke fire alarm and kept working for 30 min, during which it produced a limited-sized filament for testing. At the same time, the operator fed the crashed FDM waste manually. While a small amount of smoke was visually noted during the experiment, the room fire alarm was not triggered. The machine components were inspected before and after the experiment, and no damage was reported.

3. Results

The machine testing phase was instituted after completing the prototype assembly. The entire working procedure with each system of the machines was tested to ensure performance and safety.

3.1. Power Supply and Wiring

The machine motor requires 12 V 6 A to work appropriately and 240 V A.C. for the heating bands provided by the power supply unit, as shown in Figure 9. The wires were run through grooves of the aluminium extrusions to protect them and ensure safe aesthetics.

The power supply produced a 12.6 V D.C. constant output to support the motors with 12 V after a 0.6 V drop in the motor controllers. The main power switch installed on the display and control unit managed the power supply and the A.C. circuit.

3.2. Display and Control System

The fully assembled unit and the menu display are shown in Figure 10. The main menu has three options. Option “1” stands for extruding ABS, “2” stands for PLA, and “3” or “R” stands for cleaning cycle. The main difference between the three options is the pre-set temperature. The PLA setting has the maximum extruder temperature of 180 °C, ABS is set to 200 °C, and the cleaning cycle added to eject any previous material in the barrel is set to 240 °C.

(**A**) (**B**)

Figure 10. (**A**) Display and control system. (**B**) The main menu and extruding ABS menu.

The machine status on the bottom of the screen was changed from “Machine is not ready” to “Machine is ready” after the filament-positioning system auto-home process was completed. On this condition alone, the machine would take any input from the user. Then, the machine turned on the heating band to increase the extruder temperature to the pre-set range. Once the temperature was reached, the extruder motor and cooling fan were automatically turned on. The system status is displayed on the screen and the tested well.

3.3. Spooler System

The spooler system’s testing with the two stages of spool change can be seen in Figure 11. Stage one: An empty spool is connected to the spooler shaft and secured by tightening the spool locking mechanism. This can be achieved by turning the outer spooler lock disc clockwise. Once the spool is locked, it will rotate with the spooler shaft as the motor operates.

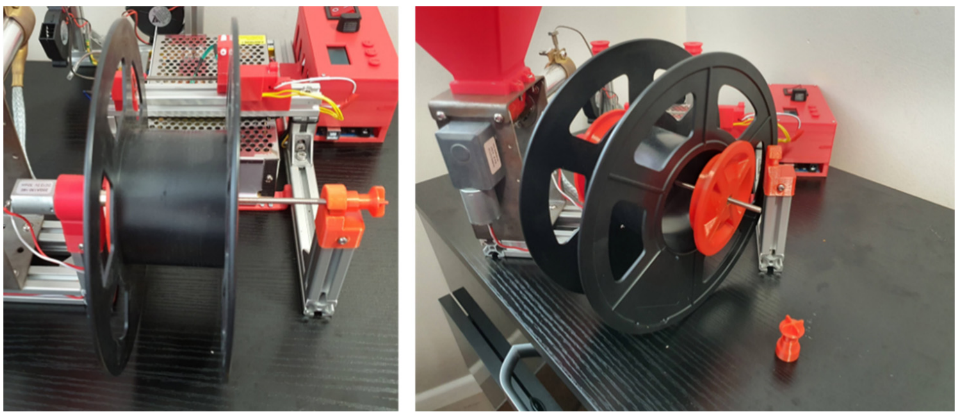


Figure 11. Left: spooler system when in operation. **Right:** spool is removed from the motor shaft.

Stage two: In order to replace the spool, firstly, the spooler-bearing lock is removed from the shaft and the bracket to release the shaft. Then, the shaft is rotated while being pulled away from the machine. The outer spooler lock disc is rotated anti-clockwise to loosen the spool. The disc is completely removed from the shaft to replace the spool. With the design of the spooler system, various spools can be used with the machine despite the difference in internal diameter. The spool's maximum inner diameter is 72 mm, and the minimum is 57.5 mm.

3.4. Filament-Positioning System

Once the machine starts to produce filament, the user must manually take the filament and run it around both V-groove pullies. The filament is later inserted through the filament break detection switch of the filament positioner and then connected to the spool. Then, option "1" has to be pressed to turn on the filament detection option with the filament-positioning system and spooler system. If the system detects a broken filament, the filament-positioning system and spooler system are automatically turned off. A buzzer will start to beep intermittently to notify the user. After pressing button "2" to reset the break detection switch, the initial filament-running procedure has to be followed. Once the rerun procedure is completed, pressing "1" will restart the systems. Pressing "R" will reset the machine and return it to the main menu.

As seen in Figure 12, the M4 threaded shaft filament break detector is driven by a 12 V gearbox D.C. motor. This is achieved by controlling the motor through the Arduino motor controller board. The motor will only run for half a second and wait two seconds before repeating the action.

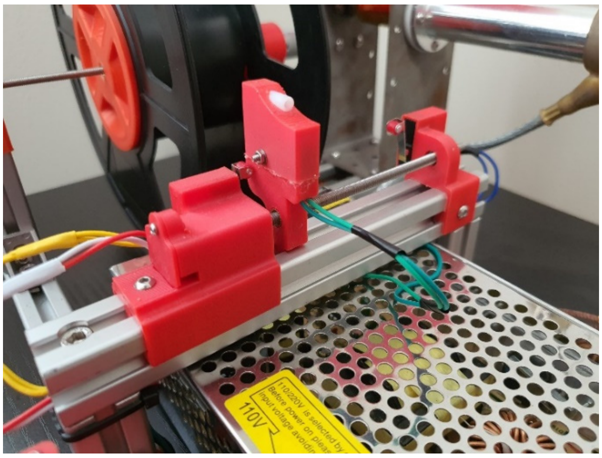
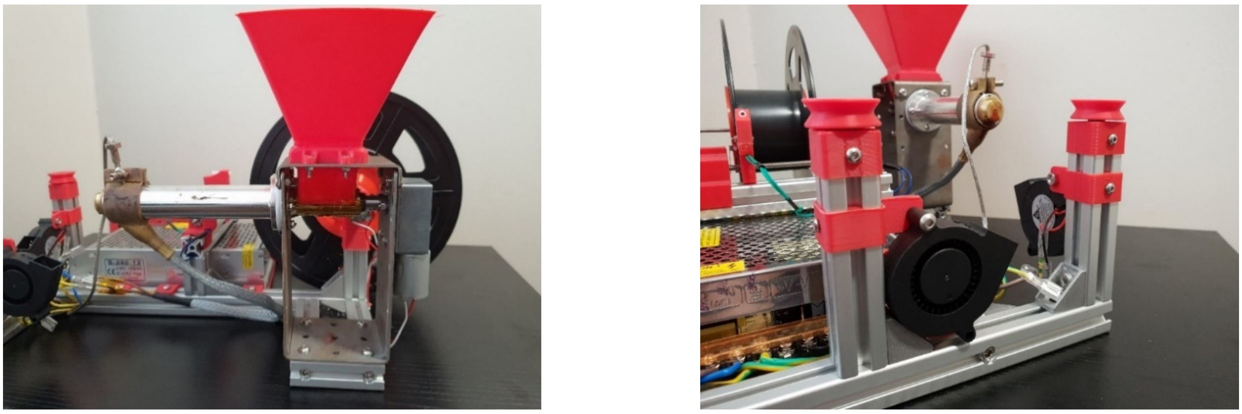


Figure 12. Filament-positioning system in the home position.

3.5. Extruder System

The extruder was tested using crushed PLA chips. Initially, the temperature for PLA was set to 200 °C. The preheating process caused the temperature to peak around 215 °C despite the heating bands being turned off. The temperature then dropped to 200 °C (±10 °C) and was maintained. This occurrence caused the extruder to produce smoke due to overheating of the PLA. The temperature was then set to 180 °C, which resolved the problem. Two cooling fans were used to direct cooled air to the filament so as to solidify the molten plastic more quickly. The fans were set to turn on with the extruder when the barrel reached the set temperature, as shown in Figure 13B.

To summarise, the machine was tested thoroughly, and the recycled PLA was produced, as shown in Figure 14. The fully assembled machine, with a spool, has a volume of 414.3 mm × 362.8 mm × 232 mm, ideally suited for a desktop environment. The machine can be shipped disassembled, taking up only 30% of the fully assembled volume.



(**A**) (**B**)

Figure 13. (**A**) Fully assembled extruder system and (**B**) two cooling fans pointing at the filament path for the cooling of the newly made filament.

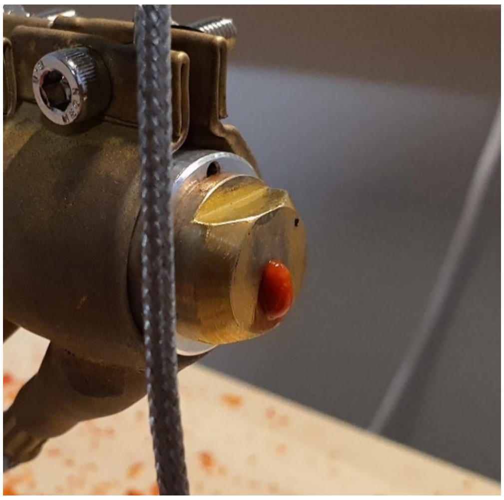


Figure 14. Extruder in operation while extruding PLA for the first time.

During the validation test, some minor issues occurred: First, the auger bit inside the barrel was not on the axis of the barrel but placed at an angle, as shown in Figure 15. Secondly, we found that varying sizes and shapes of the PLA chips might cause the extruder motor to stall, leading to a poor final product outcome.

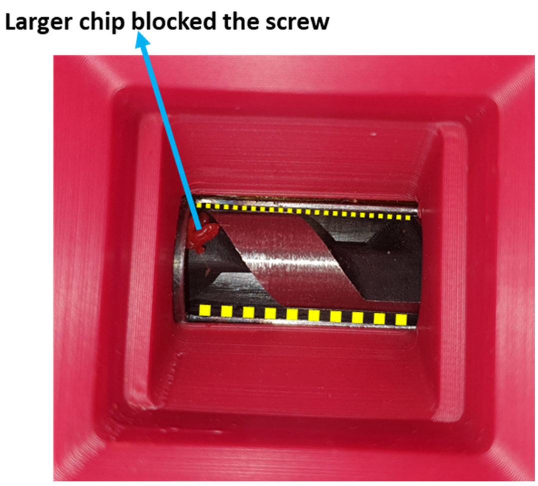


Figure 15. The auger bit position (the thickness of the yellow lines indicates the width of the gap).

4. Discussion

The prototype of the 3DP-MRM was completed, with all systems working as expected with minor problems. The issue with the varying size of the chips is due to the fact that the chips in the barrel collector did not have a consistent size and could become stuck in the gap between the auger bit and the barrel collector tube, causing the extruder motor to stall. As seen in Figure 16, type-A chips are larger than type-B chips, where type-A includes larger and flatter chips that have higher probabilities of falling into the gaps between the auger and the chip collector tube that needs to be filtered. Shredding plastic to the required sizes was a challenge which caused the termination of the testing of the extruder system. With properly shredded and filtered plastic, the machine should be able to produce continuous filaments.

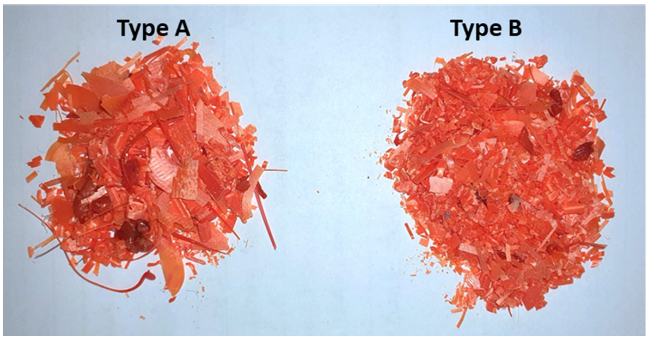


Figure 16. Type (**A**) larger PLA chip size and type (**B**) ideal chip size for extruding.

A challenge faced during the machine assembly was that parts were not aligned as they were designed. Regarding the auger bit, it was not placed on the barrel axis, mainly due to the fact that the extruder brackets made from sheet metals had flanges that were not parallel, a result of the sheet-metal-bending process. This caused additional friction between the auger bit and the barrel interior wall. Avoidance of this misalignment would improve the auger bit movement and reduce the gap, which would help to push the chips to the nozzle. As seen in Figure 17A, the design was intended for the parts with minimum to no gap for the chips to fall. Figure 17B revealed a 3 mm gap when the parts were assembled due to differences in the sheet-metal-folding angle and flatness of the sheet, which could cause the chips to fall. The easiest fix to solve this issue that can be used for this prototype is to cover the gap using high-temperature-resistant PTFE tapes. While the current prototype has many synchronised processes, as seen in Figure 18, future design or manufacturing improvements could be applied.

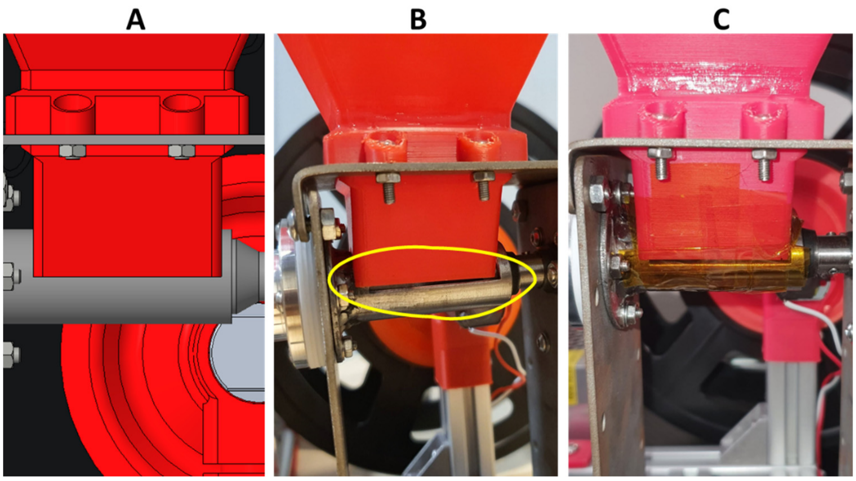


Figure 17. (**A**) CAD model of the chip collector and collector tube. (**B**) Gap between the chip collector and tube shown in a yellow circle. (**C**) High-temperature-resistant PTFE tape is used to cover the gap.

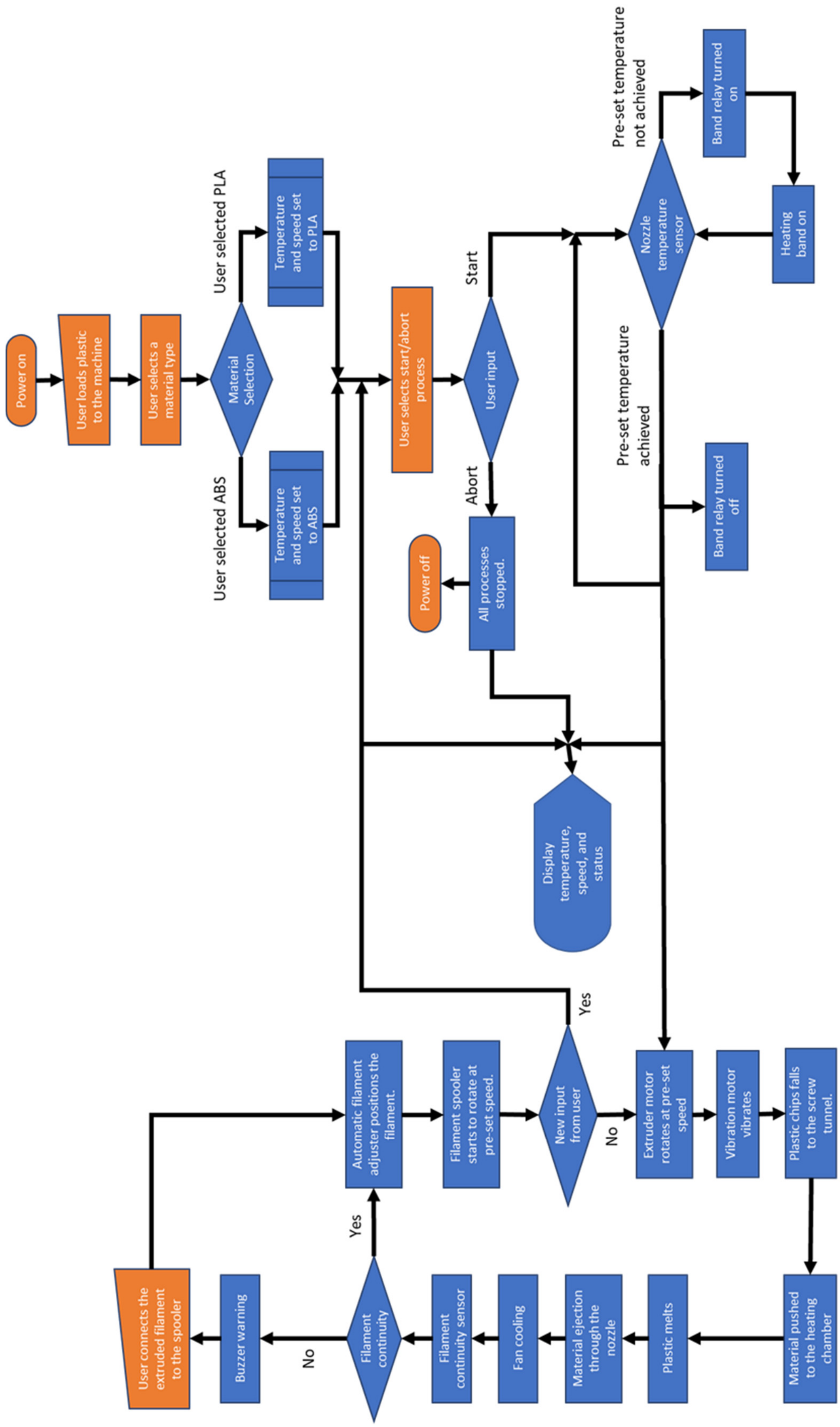


Figure 18. 3DP-MRM workflow chart.

Aside from the manufacturing issues, the prototype cost is calculated to be GBP 908, which is relatively expensive, including the production and workshop service fee of GBP 590, purchase fee of GBP 268 m for the other parts, and miscellaneous fees of nearly GBP 50. However, cost savings must still be considered for the product, even in the testing stage. The largest amount of money spent on this project was for the manufacturing of barrels and other sheet metal parts in the workshop; such expenses should be decreased in cases of mass production. To justify the development of the machine, the cost of the final product has to be explained and understood. When the mass production of parts is considered, it should decrease the costs. Continuous production can be cheaper than producing just one part. With this consideration, the cost of the barrel cap can be reduced to GBP 7.36, and the extruder bracket can be decreased to GBP 11.79, which demonstrates the possibility that the machine could be introduced into the market with a lower final cost and price.

Using a lower-powered power supply can reduce the overall cost of the product. The user can replicate all the 3D-printed parts of the machine, allowing the manufacturer to reduce the cost by making the STL files of the 3D-printed parts available to the customer. Customers can print and assemble the components themselves, bringing the price down. Any prints that fail during manufacturing can be recycled with the same machine. Future cost reductions should be considered.

Undoubtedly, the consistent difficulty in building 3D facilities for research purposes and the ability to produce these facilities at an economical cost can be cracked by introducing practical cost analysis to research projects. Hence, technology-improvement-based projects are being proposed by the University of Liverpool to achieve net-zero carbon by 2025. The current study opens the door to the cost-effective technology of recycling FDM 3D printing waste, which is relatively abundant in research institutions because of the nature of their research-based projects. This study's results could help to form a future strategy of filament refill schemes, where 3D-printing filament manufacturers offer refill procedures where customers can send back empty filament spools for refilling.

It is also important to mention that the recycling of FDM materials typically involves the separation of different types of thermoplastics to ensure compatibility during the recycling process. Mixing incompatible materials can result in a poor print quality or even damage the 3D printer. Moreover, the quality of recycled filaments can vary depending on the effectiveness of the recycling process. Contamination with foreign objects, debris, or incompatible materials can affect the mechanical properties and performance of the recycled filament. To maintain filament quality, it is essential to carefully clean and sort the materials before recycling them.

5. Conclusions

This study aimed to develop a material-recycling machine to reuse the thermoplastic materials used in the FDM additive manufacturing process and enable their recycling. The study achieved this aim by completing the following objectives: A plastic-recycling machine concept was developed using CREO Parametric software with a simple user interface, and a prototype was manufactured in-house to test the concept. The machine allows the user to recycle the plastic waste through 3D printing and make new filaments. The prototype was completed successfully. The filament-recycling machine was tested, and the machine worked successfully among all the designed functions, with a few minor issues.

The overall development cost of the machine was calculated to be GBP 908. This cost is relatively high, as this is a one-time prototype machine; however, most of the cost was a manufacturing cost that could be reduced by considering mass production. Further development and testing could improve the machine's capabilities, and mass-produced components could reduce the overall cost.

Lastly, it is worth noting that while the recycling of FDM materials can help to reduce waste and promote sustainability, the process is still evolving, and the quality and reliability of the recycled filament may not match that of the virgin filament. Therefore, it is essential to consider the specific requirements of 3D printing projects when deciding whether to use recycled materials or to opt for new filaments.

Author Contributions: M.N.N.: data curation, writing—initial draft, writing—review and editing, visualisation, conceptualisation, formal analysis, software, Z.R.: writing—initial draft, writing—review and editing, visualisation, A.A.: writing—initial draft, writing—review and editing, conceptualisation, project administration, resources, supervision, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded from the School of Engineering, University of Liverpool, UK MSc projects budget of the academic year 2021–2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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