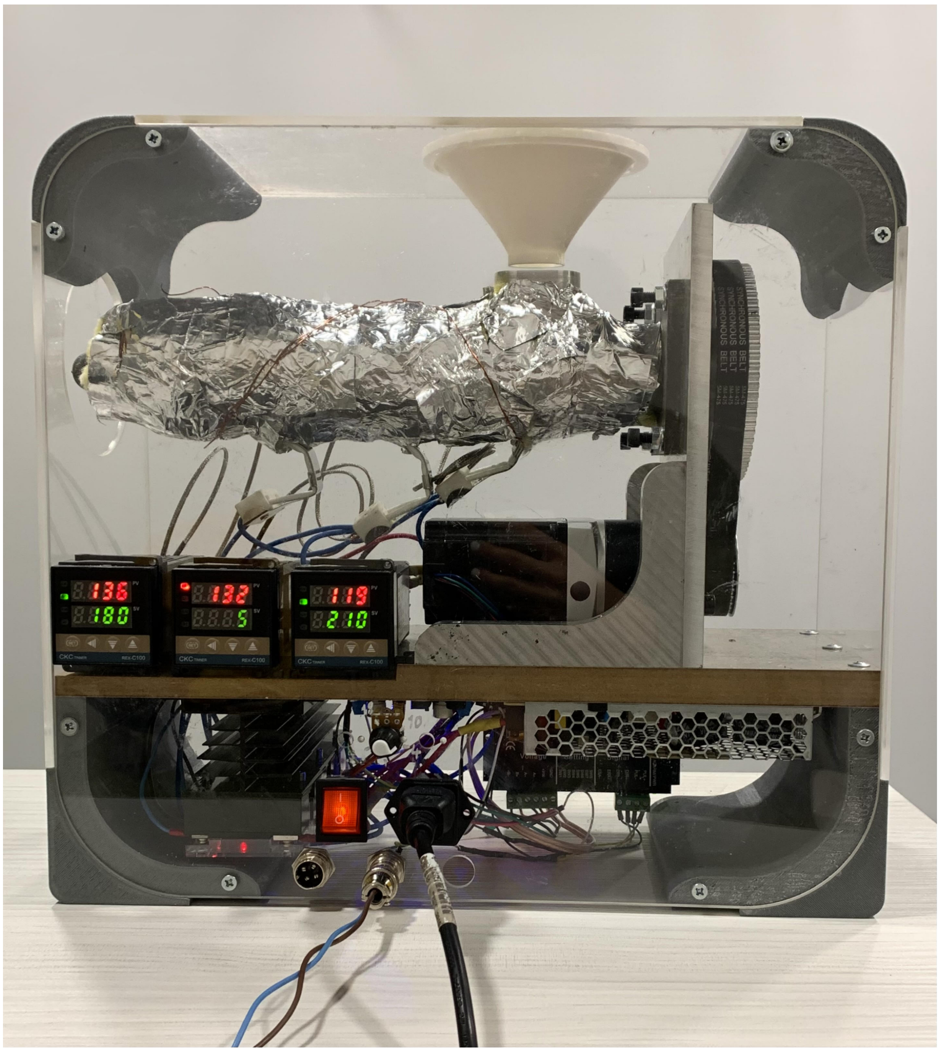

3D Printer Filament Recycler Machine

Students: Victoria Harutyunyan, Nareh Vartanian
Supervisor: Arman Asatryan
Advisor: Sargis Zeytunyan

American University of Armenia
College of Science and Engineering

+Concept of Operations (ConOps)

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1.0 Introduction

1.1 Project Description

A significant factor in the increasing popularity of 3D printing technology is the wide range of useful benefits it provides to its customers. 3D printing is becoming a highly sought-after manufacturing option due to factors like cost effectiveness, adaptability, durability, and others. However, while the waste created by 3D printing is less compared to traditional manufacturing methods, it still results in financial disadvantages for the user in the long term. Hence, this project targets the problem of 3D printing waste by offering recycling as a solution that will mainly benefit the user financially and, to a lesser extent, help the growing problem of plastic waste. This project aims to create a 3D printer filament recycler, designed and built in a way that can be easily used in both maker spaces and homes. It can be used to recycle both 3D printed waste and waste generated from other sources made from ABS or PLA, which are commonly used 3D printing filament materials. The recycled waste can be used as a filament for 3D printers. The project's goal is to make it possible to create filament easily while maintaining quality and properties high enough that will enable usage for the 3D printers using plastic waste, failed prints, pellets from recycled ABS and outdated models, focusing on reducing waste while simultaneously helping users save money.

1.1.1 Background

Even though additive manufacturing and prototyping, which 3D printing is best suited for, can help save time and money, the plastic filaments used in 3D printing add to the world's rising waste problem. Reports indicate that 242 Mt of plastic garbage was generated globally in 2016. (Kaza and Yao, 2018, as cited in Liang, 2021). Only 9% of the estimated

6.30 billion tons of plastic garbage created between 1950 and 2015 was recycled, leaving more than 80% of it to accumulate in landfills or the environment (Brooks et al., 2018, as cited in Liang, 2021). Not only does plastic waste cause the world economy to lose between $80 billion and $120 billion annually, but it also harms the environment as it is estimated that by 2050 there will be more plastic than fish by weight in the oceans (MacArthur, 2017).

3D printing may be made more environmentally friendly in a number of ways, including recycling unsuccessful prints. Recycling filament from 3D printers that have been previously used might be another option. Two of the most common material types used in 3D printing are PLA and ABS; however, many of our daily appliances are made from those two materials as well. ABS material can be found in musical instruments, kitchen utensils, vacuum cleaners, plastic toys, etc. While PLA can be found in medical applications, including implants.

1.1.2 Methodology

Research:

1. The first step in the development of a methodology was the identification of the problem and gaining an accurate understanding of it.
2. A blended approach of both qualitative and quantitative research was used in order to learn about the available information on the topic at hand.
3. Obtained info was narrowed down, and only applicable documents were kept.
4. More detailed information was collected about the need for filament recycling and materials used as a filament from face-to-face interactions with local 3D printer users.
5. Webinars and meetings were attended on the topics of 3D printing, sustainability through plastic reshaping, and the benefits of using ABS filament for 3D printing.

6. More information was obtained about the existing extruders and their working specifications.
7. The datasheets of the electronic components were thoroughly explored and used during the assembling and wiring processes.

Implementation:

1. The initial device structure was defined based on existing models.
2. Different modules needed to implement the system's goal were specified.
3. The general sketch was drawn by hand to visualize the idea of a system.
4. The bill of materials (BOM) table was created and provided to AUA.
5. The 3D model was created with SOLIDWORKS software to have a better understanding of the system before the delivery of the components and the assembly of the final device.
6. Detailed 3D models were created for 3D printing, CNC machining, and laser cutting.
7. After the arrival of the components and after the structural parts were 3D printed, shaped with a CNC machine, or laser cut, the system was assembled.
8. The layout of electronic components was created, and based on the layout, the wiring diagrams were made.
9. Once the wiring diagram was approved, the actual wiring was done, and the electronic components were tested.
10. An Arduino code was written in order to test the motor and motor driver.
11. Detailed Arduino code was written to change the speed of the motor using a potentiometer.
12. In order to test the system safely, the extruder was insulated using fiberglass.

13. The system was tested, and the existing bugs were fixed.
14. After fixing the bugs, various experiments were conducted by changing the parameters of the heat controllers and the potentiometer to obtain results.
15. The results were analyzed based on the experiments, and the most optimal parameters that provide acceptable quality of the filament were established.

1.1.3 Assumptions and Constraints

Assumptions:

- It was assumed that all the necessary components would be obtained by the end of the first month of the spring semester so that the assembling, testing, and experiments could be conducted.
- It was assumed that the components for the system would be obtained with the help of the American University of Armenia.
- It was assumed that we would have access to the AUA's lab's tools and equipment as well as waisted 3D printer parts.

Constraints:

- In order to have a printable filament to test with the available printers in the AUA lab, the produced filament should have a diameter of 1.75mm $\pm$ 0.05mm.
- The availability of all the necessary parts and conditions to test the system.

1.2 Overview of the Envisioned System

1.2.1 Overview

The 3D printer filament extruder is a system that uses ABS recycled plastic pellets as an input, and the output is a filament that can be used in 3D printing. The process consists of several steps and modules. The main modules are extrusion and cooling and spooling. At first, the plastic waste is ground to obtain small granules (pellets), which will be fed to the extrusion line. It is important for the pellets to be consistent in size in order to avoid complications later in the melting process. Then the pellets should be dried as ABS absorb moisture which can result in bubbles in the extruded filament and affect its quality. In the next step, the pellets are fed to the extruder through a hopper. In the extrusion module, the pellets are melted by heaters and extruded by the movement of the screw as filament through a nozzle. The filament is then cooled and wrapped around a spool with the help of the puller module and is ready to be used for 3D printing.

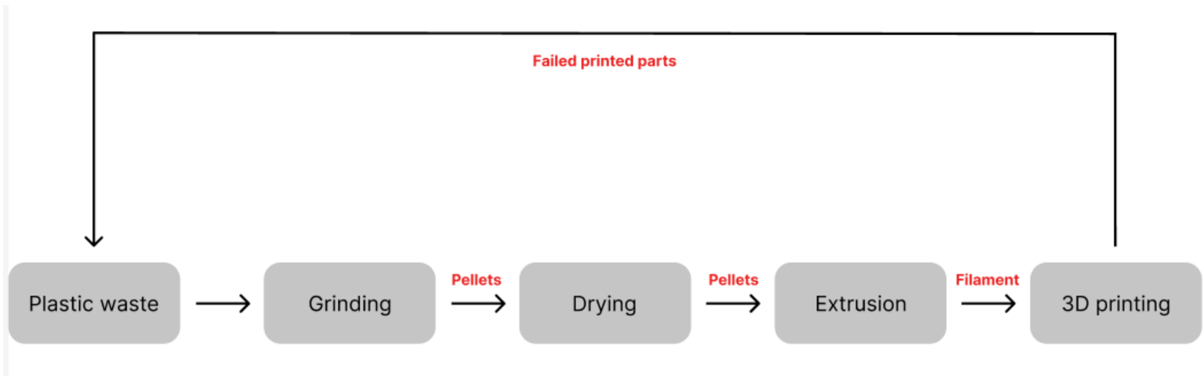

Fig. 1 Conversion of waste plastic to 3D printed parts

1.2.2 System Scope

This is a multidisciplinary project that requires knowledge and application of various fields such as mechanical and electrical engineering, CAD, 3D printing, CNC machining, Arduino programming, chemistry, and environmental engineering. It aims to create a compact system, yet it will integrate all the necessary components. The envisioned system consists of mechanical components such as barrel, screw, pulleys, fasteners, and electrical components such as motors, motor drivers, heaters, controllers to control the heaters, solid state relays, switches, potentiometers, and Arduino. The experimentation process was done using pellets from recycled ABS plastic as a shredder is considered as an external enabling systems that lies outside the project's scope. However, in case of the availability of the shredder, the experiments can be done using shredded plastic.

2.0 Documents

2.1 Applicable Documents

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Pakkanen, J., Iuliano, L., & Minetola, P. (2017, April). About the use of recycled or biodegradable filaments for sustainability ... Retrieved December 1, 2022, from https://www.researchgate.net/publication/316465179_About_the_Use_of_Recycled_or_Biodegradable_Filaments_for_Sustainability_of_3D_Printing

ShanZhonga, & M.Pearce, J. (2017, September 29). Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with Recyclebot and RepRap 3-D printing. Resources, Conservation and Recycling. Retrieved December 21, 2022, from https://www.sciencedirect.com/science/article/abs/pii/S0921344917303014

2.3 Datasheets

10:1 Planetary Gearbox Nema 23 Stepper Motor Datasheet:
https://www.omc-stepperonline.com/index.php?route=product/product/get_file&file=565/23HS22-2804S-HG10_Full_Datasheet.pdf

10:1 Planetary Gearbox Nema 23 Stepper Motor Torque Curve:
https://www.omc-stepperonline.com/index.php?route=product/product/get_file&file=565/23HS22-2804S-HG10_Torque_Curve.pdf

CWD556 Digital Stepper Drive Datasheet:
https://www.circuitspecialists.com/content/125505/CWD556.pdf

REX-C100 Heat Controller User Manual:
https://www.rkcinst.co.jp/english/downloads/8933/imnzc22e1/

3.0 Description of Envisioned System

3.1 Needs, Goals and Objectives of Envisioned System

Goals:

The main goal of the system is to produce a filament from recycled plastic with quality high enough to be able to use in 3D printing. The quality of the filament is mainly based on the consistency of the filament and its diameter. The standard diameter for 3D printer filament, which this system aims to achieve with minimal errors, is 1.75mm. The diameter accuracy is based on several factors, such as heating temperature, cooling, motor speed, measurement accuracy, and human error. When used in a 3D printer, an inconsistent filament diameter might cause significant problems. Extruder failure, in which the extruder malfunctions and no plastic reaches the hot end, is a common instance. This could happen if the filament suddenly becomes too thin for the extruder tensioning system, which results in the filament not being gripped tightly enough. On the other hand, when the filament suddenly has a diameter that is too large, making it is impossible for the extruder motor to force it through the hot end opening.

Another goal is for the system to be as compact, durable, and reliable as possible. Using a single frame for both the extrusion and main electronic components will make the system more compact and portable and will make maintenance easier.

Objectives:

The system's main objective is to reduce financial loss from wasted filament for individuals that are using 3D printing since long-term printing costs are much lower when the filament is recycled. By recycling plastic wastes to create filament for 3D printing, this project aims to popularize the ideas of distributed recycling, circular economy, and frugal engineering. Distributed recycling, which allows consumers to recycle their own waste instead of sending it to a traditional recycling facility, has the potential to use less energy because it can eliminate the need for the transportation that is required for traditional recycling (Arena et al., 2003, Ross and Evans, 2003, as cited in Zhong, 2018).

3.2 Overview of System and Key Elements

The project's main focus will be developing the filament extrusion device whose key elements are an extrusion module, a cooling module, and a spooler. The extrusion module consists of an auger or a screw, a hopper, a barrel, heaters, and a nozzle (Fig. 2). The rotation of the screw is provided by the motor gearbox with the help of a pulley attached to it. The screw physically moves the plastic pellets through the barrel as the temperature of the heaters gradually increases, making the pellets melt. The molten plastic is then extruded through a nozzle. Meanwhile, the plastic pellets are continuously fed to the module through the hopper. The extruded filament is then passed through the cooling module, which is hardened. The cooling process could be done through air or liquid. In this system, a cross-flow fan is used for the cooling process. When the filament leaves the nozzle, it is still very hot and flexible. Cooling is crucial to keep it from expanding excessively due to the impacting g-forces when falling down. In order to achieve an optimal diameter for the filament, a potentiometer is used to control the motor speed, and controllers are used to control the heating temperature. After the filament reaches the desired diameter and the diameter is stabilized, it will be wrapped around a spool manually.

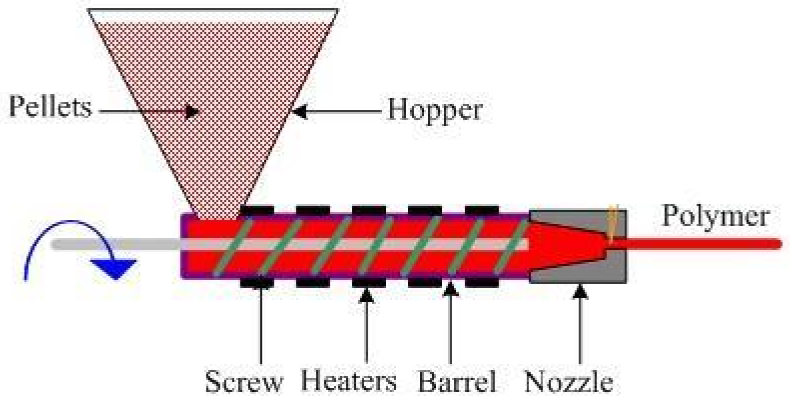

Fig. 2 Parts of the extruder module

3.2.1 Hardware key components of the extrusion module:

Main Structural Support Elements:

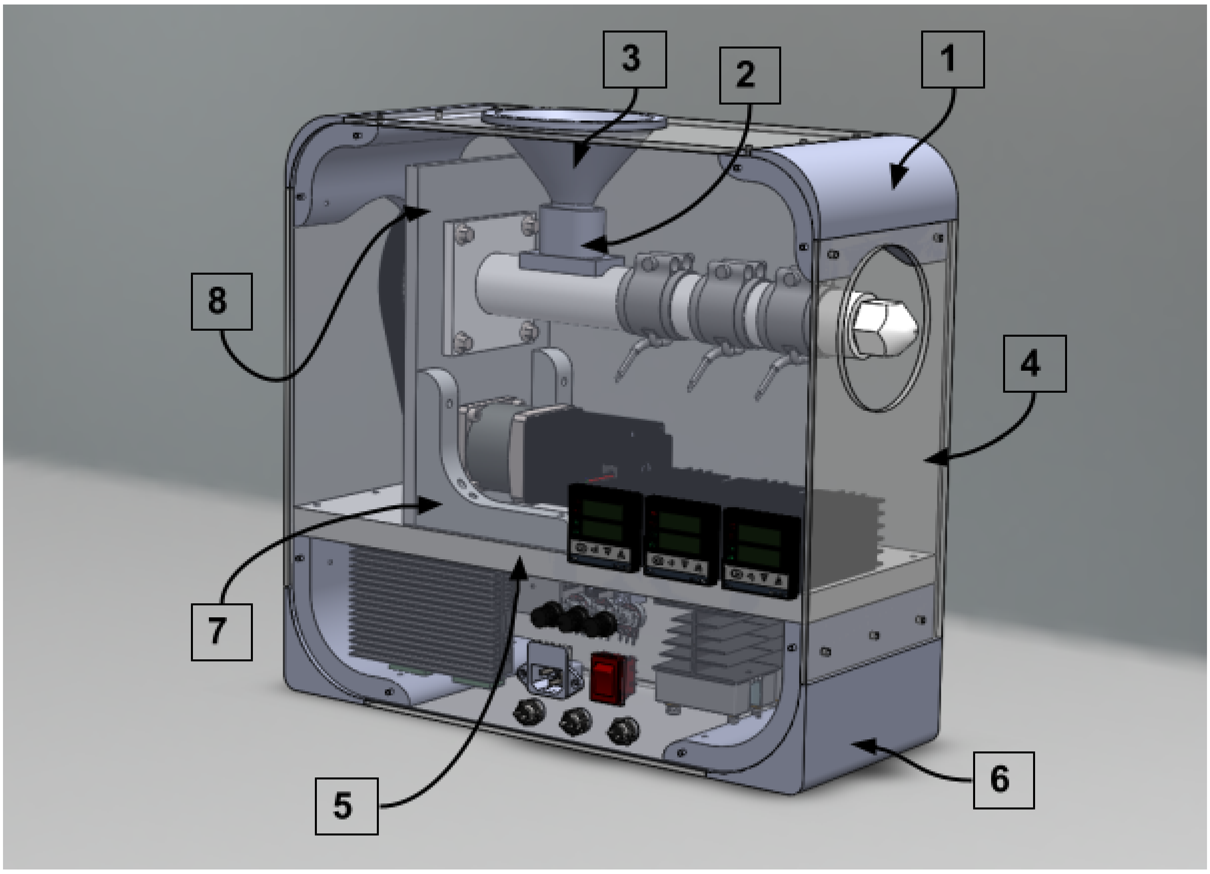

Fig. 3 3D model of the extruder created with SOLIDWORKS highlighting the main structural support elements. The specs of the elements marked with the numbered boxes can be found in the Table 1 below

Part	Quantity	Produced/Machined by
1) Upper Corner	2	3D Printer
2) Hopper Base	1	CNC
3) Hopper	1	3D Printer
4) Plexiglass	5	Laser Cutting and CNC
5) MDF Base	1	CNC
6) Bottom Corner	2	3D Printer
7) Support Ribs	2	CNC
8) Mounting Plate	1	CNC

Table 1 The specs of the main structural support elements shown in Fig.3

Main Electrical and Mechanical Components:

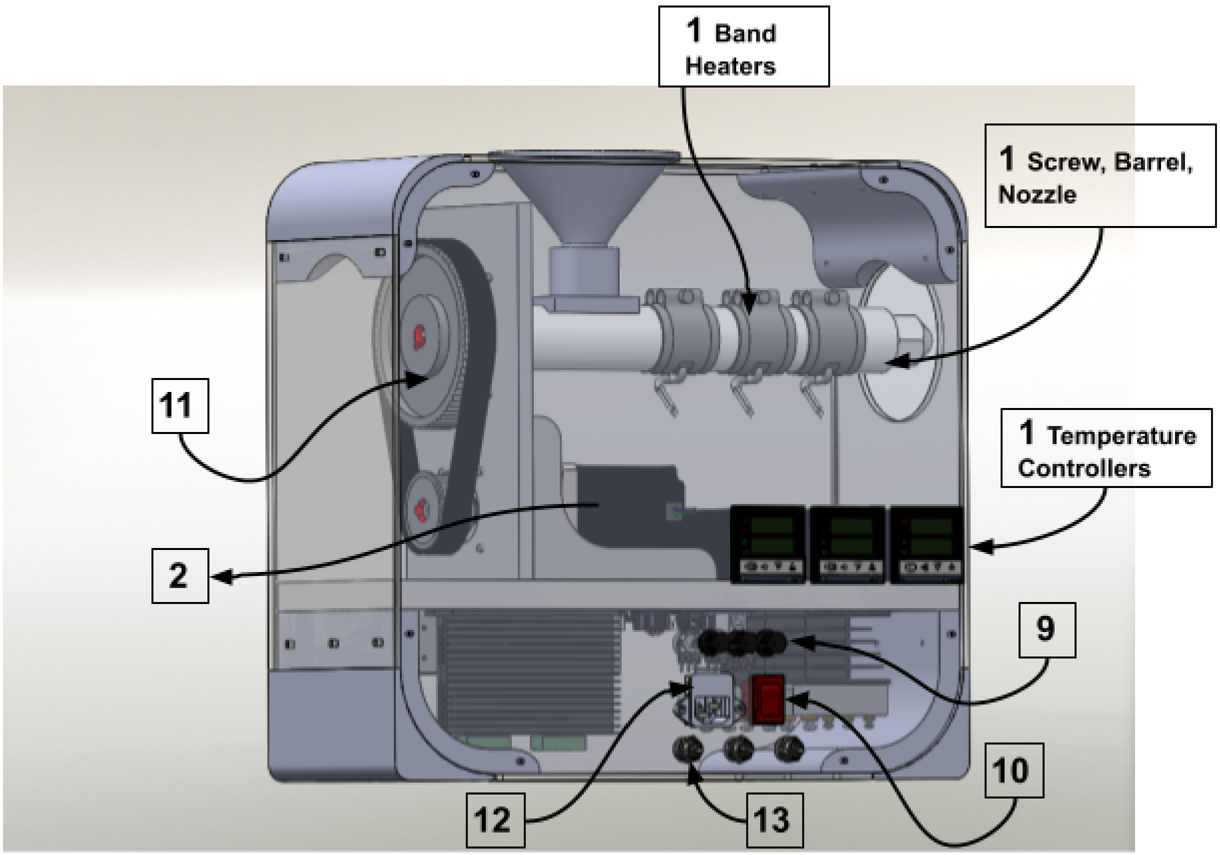

Fig. 4 3D model of the extruder created with SOLIDWORKS highlighting the main electrical and mechanical components. The specs of the elements marked with the numbered boxes can be found in the Table 2

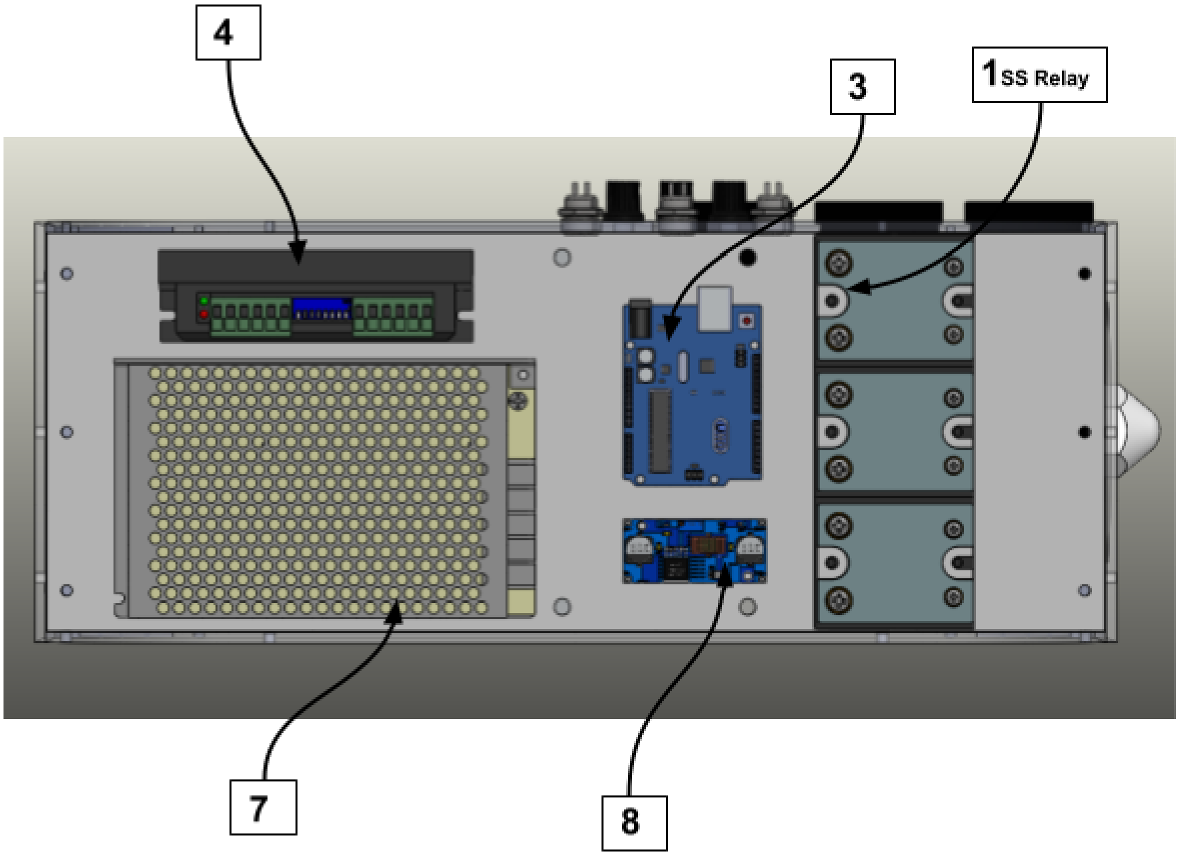

Fig. 5 The layout of electronic components created with SOLIDWORKS. The specs of the elements marked with the numbered boxes can be found in Table 2

Screw, barrel, and nozzle: this set is suitable for our project for the following reasons:

- Small screw and barrel diameter appropriate for commercial extruders. In the case of a larger barrel and screw diameter, there would be a risk of air-bubble development in the filament
- 1.75 mm nozzle applicable for testing with the 3D printer available at the AUA's lab. Also, if needed, the diameter can be increased for better results.

Band heaters, thermocouples, PID temperature controllers, solid-state relays (SSR), and SSR heatsinks: these components are used to produce and control the heat needed for melting the pellets. The following characteristics make them a correct choice for the project:

- The band heaters have the capability of being fastened on the barrel and produce very high temperatures.
- The controllers enable the user to adjust the temperature of the band heaters based on the feedback from the thermocouples.

- The solid-state relays turn the heaters on/off according to the instruction from the controllers.
- The heatsinks cool the SSRs, keeping their temperature in the operating range

Planetary gearbox Nema 23 stepper motor:

- The gearbox decreases the load-to-motor inertia ratio, which allows the stepper motor to control the load (the screw) more efficiently.
- The gearbox increases the torque available for the motor to rotate the screw.

Motor driver:

- Allows the control of the motor (speed and direction) with a microcontroller.
- Drives the high-current stepper motor with a low-current logic circuit.
- Provides the option to have smaller micro steps, which enables smoother motor operation.

Part	**Mission**	**Specs**	**Quantity**	**From**
1) **20mm Dia Extruder Screw Kit with Temperature Control System**	To melt, push, and extrude the plastic under controlled conditions	**For band heaters** Rated Voltage: 220V Power Rating: 150W **For PID controllers** Rated Voltage: 220V	1	Link
2) **10:1 Planetary Gearbox Nema 23 Stepper Motor Φ14mm**	To rotate the screw inside the barrel	Rated Current/phase: 2.8A Rated Input Voltage: 24-48VDC	1	Link
3) **Arduino Uno R3 Microcontroller**	Programmable device to control the interaction between different components	Input Voltage: 7-12V Operating Voltage: 5V	1	borrowed
4) **CWD556 Digital Stepper Driver**	To drive the Nema 23 stepper motor	Input Voltage: 20-50VDC Output Current: 0-5.6A	1	borrowed

		Pulse Signal Frequency: 0-200 KHZ		
5) Cross Flow Fan	To cool the filament after extrusion	Input Voltage: 12VDC Rated Current: 0.3A	1	borrowed
6) A4988 Stepper Motor Driver	To drive the Nema 17 stepper motor	Operating Voltage: 8-35VDC Continuous Current per phase: 1A	2	Purchased
7) Power Supply 24V DC	To supply power to different components	Input Voltage: 200-240V Output Current: 8.33A	1	Purchased
8) 24V to 12V DC-DC converter	To step down the DC voltage from 24V to 12V	Input Voltage Range: 20-30VDC Output Voltage Range: 12V-13.8VDC	1	Purchased
9) Potentiometer	To PWM control the stepper motors	Resistance: 20Kohm	3	Purchased
10) 6 Pin Rocker Switch	To turn the recycler on or off	-	1	Purchased
11) 3:1 Ratio Timing Belt Pulley	To increase the torque and translate the motion from the motor to the screw	-	1	borrowed
12) Electrical AC Power Socket Male Connector	To provide AC power to the system	Rated Voltage: 250V Terminals: 3 Pin	1	borrowed
13) 2 Pin Round Shell Aviation Connector	To connect the cooler to the 12V DC power supply placed inside the extruder	-	3	Purchased

Table 2 The specs of the main mechanical and electrical components shown in Fig.4 and Fig.5

3.2.2 Hardware key components of the cooler module:

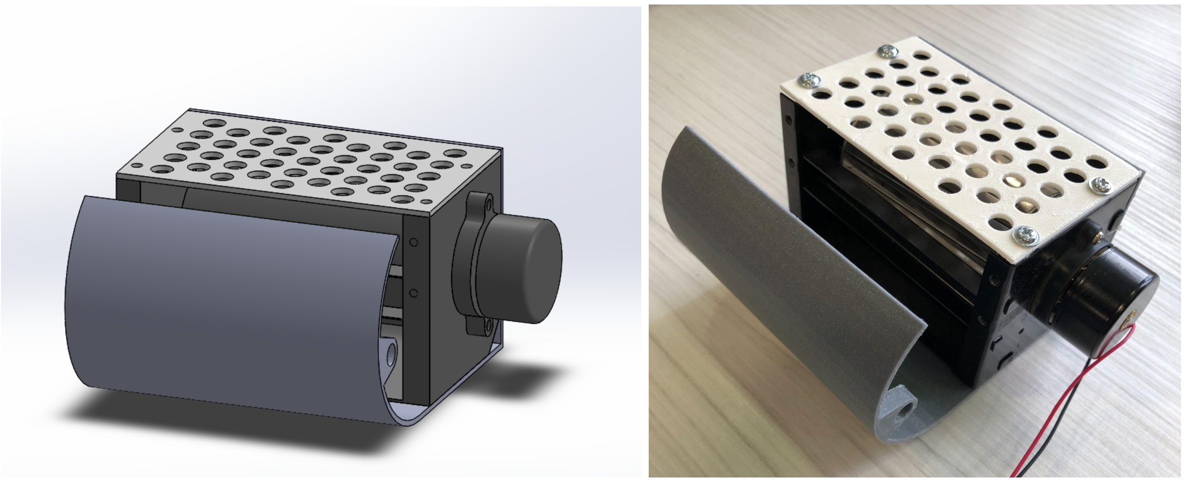

Fig. 6 The image on the left is a 3D model of the cooler module created with SOLIDWORKS and image on the right is the cooler module with 3D printed parts

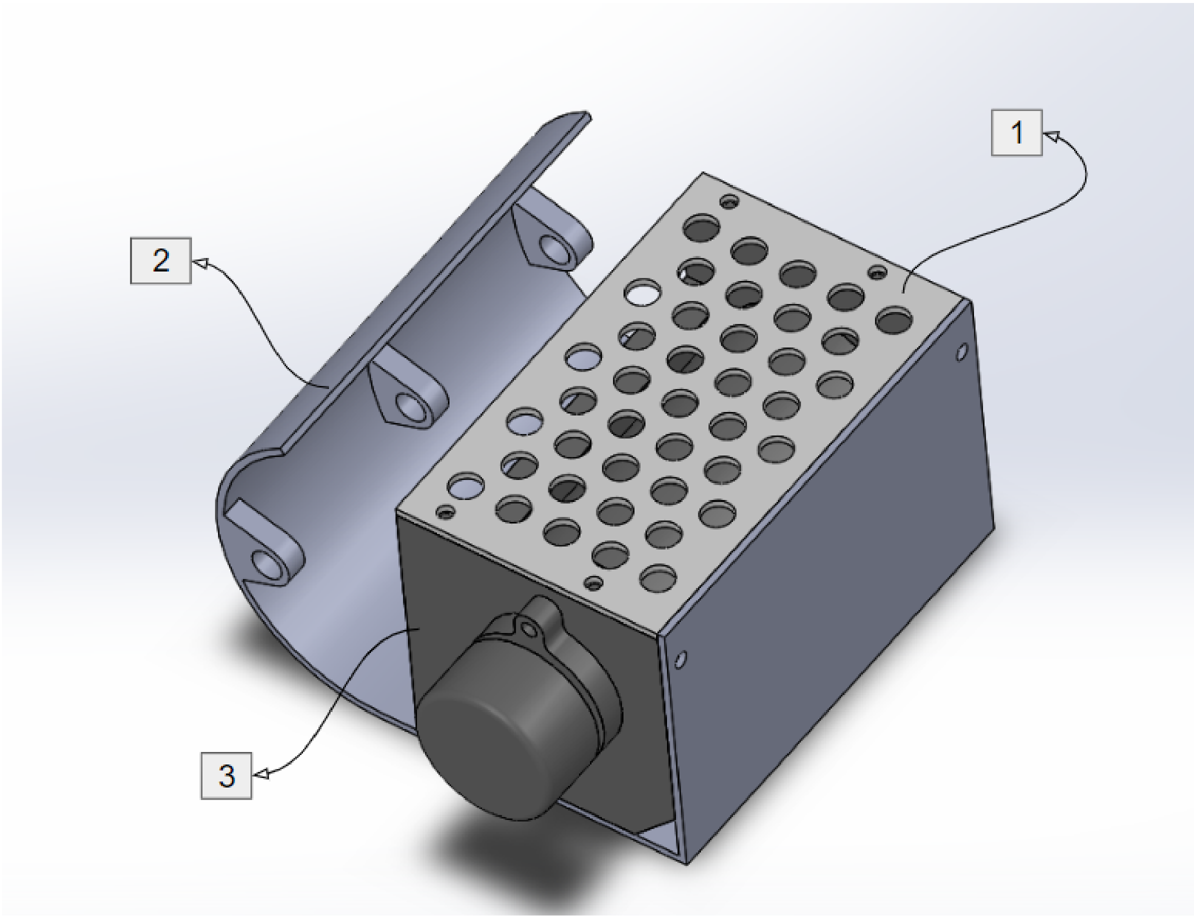

Fig. 7 3D model of the cooler created with SOLIDWORKS highlighting the main structural parts

1. The upper part of the cooler assembly that enables air circulation and protects the user from getting accidentally injured by the fan. The part is made from ABS and is printed in the AUA engineering lab with a 3D printer.
2. Main frame for the fan is made from ABS and is printed in the AUA engineering lab with a 3D printer. The holes enable the user to guide melted plastic through them while the fan is on. The gaps between the holes make it possible for the air from the fan to blow directly into the melted plastic and thus providing cooling.
3. The cross-flow fan which has an impeller. When the impeller rotates, the air enters the blades from the open part of the fan and, after circulation, exits from the front where the filament is situated.

3.3 Interfaces

The main interfaces of the system are the ON/Off button which starts the system, the potentiometer, which controls the speed of the motor, and the heat controllers.

The display of a PID controller enables the user to set the desired temperature (marked with SV) and see the measured temperature (marked as PV), which changes according to the set temperature value. Fig. 8 below shows the display of the PID controller used in this system.

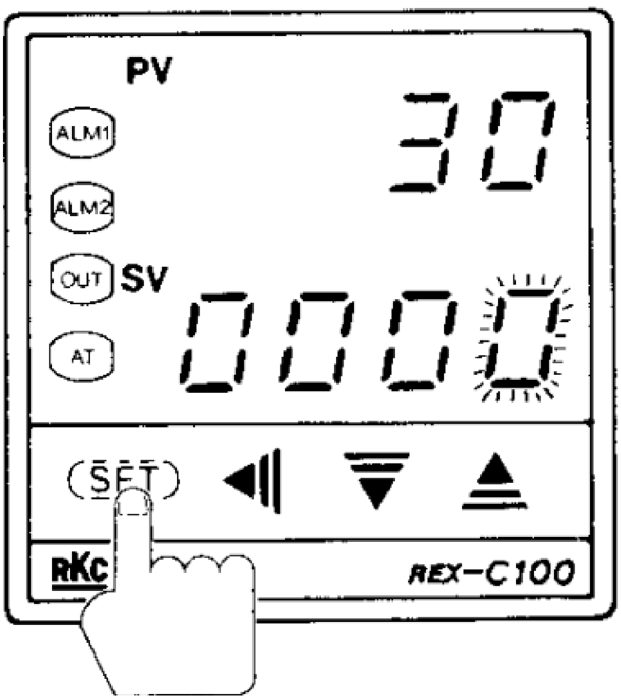

Fig. 8 The Display of the PID Controller

3.4 Electrical Wiring

Powering:

The system is turned on using the ON/OFF 6 Pin Rocker Switch. The two pins of the switch are connected to 220V AC and supply the 220V AC to the 24V power supply, the band heaters, the PID temperature controllers, and the solid-state relays.

The Nema 23 stepper motor driver and the DC-DC converter are powered by the 24V power supply. The Arduino and the fan are supplied by 12VDC from the DC-DC converter, and the stepper motor is supplied 24V through the stepper driver.

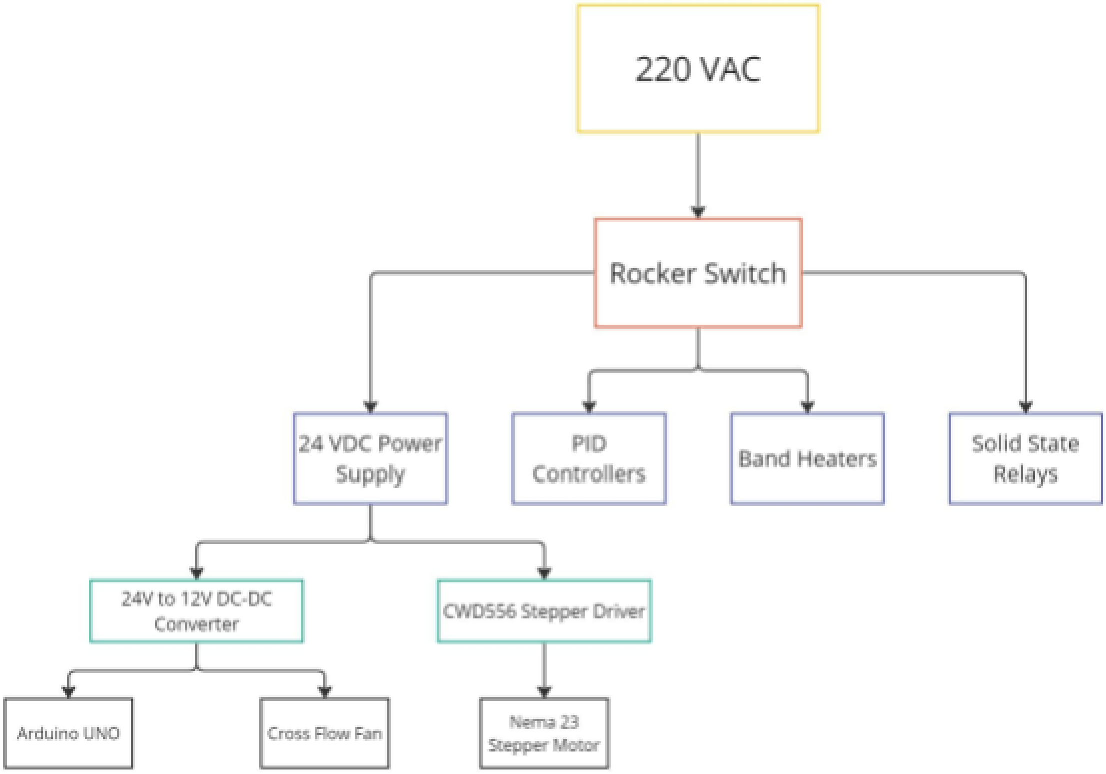

Fig. 9 Scheme of Power Transmission

Heating:

The wiring for the heating part was done according to the diagram below. The Thermocouple, which is connected to the barrel and the heat controller, provides feedback about the actual temperature at the barrel. Based on the data, the heat controller either turns the relay connected to the band heater on or off in order to achieve the desired temperature value.

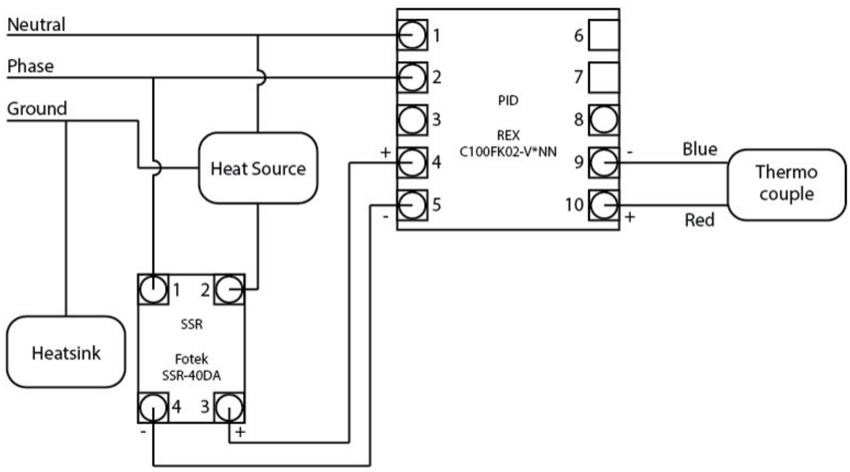

Fig. 10 The wiring diagram of the heating elements derived from the link.

Motor Control:

According to Fig. 11 The stepper motor driver is connected to Arduino's corresponding pins and to the motor. A potentiometer is used to control the speed of the motor. One of its pins is connected to Arduino's analog input pin, and the other two pins are correspondingly connected to the Arduino's 5V supply and the ground. The analog pin of the Arduino receives voltage ranging from 0-5V from the potentiometer, which using a mapping function in Arduino code, controls the delay between the steps of the stepper motor, resulting in faster or slower speed based on the value received by the potentiometer. The Arduino code can be found using the github link. The maximum speed of the motor is set to be approximately 1050 rpm, and the speed range of the screw is 0 rpm-35 rpm as a motor gearbox with a 10:1 gear ratio and a pulley with a 3:1 ratio are used in the system.

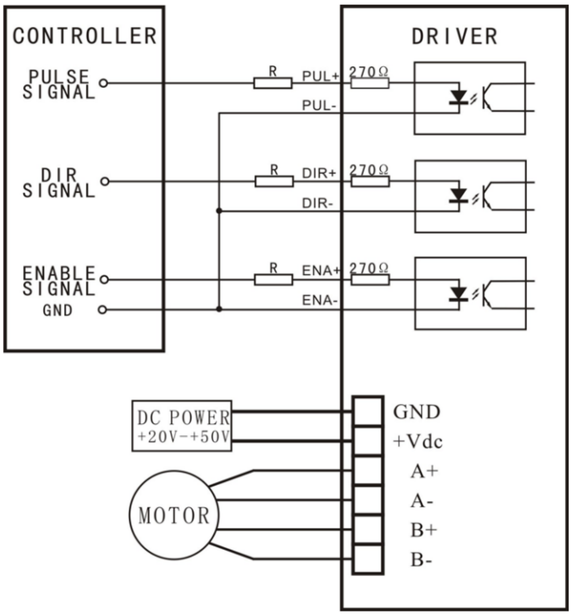

Fig. 11 Connection of the CWD556 stepper driver derived from the datasheet

3.5 Modes of Operations

One of the main challenges of the system is to provide and maintain specific diameter and homogeneity of the filament, which is needed for the filament to be usable by 3D printers. The temperature of the heater and the motor speed are the primary aspects that affect the modification of the diameter of the final filament. Firstly, by changing the temperature values of the three heaters, the optimal temperatures were found. Temperature values higher than the optimal ones cause bubbles in the filament, making the quality low. In contrast, the temperature values lower than the optimal ones make the filament sticky and not adequatly melted, again leading to a bad quality. In addition to the temperature values, the different values for the speed of the screw were marked around the potentiometer, so the user, experimenting with different speeds, could find the optimal one.

3.6 Order of Operations

1. Make sure the potentiometer is on zero.
2. Plugin the device and turn the switch on
3. Without running the motor, set the desired temperatures of the heaters using the heat controllers.
4. Wait until the temperature of the heaters matches the desired temperature.
5. Turn the potentiometer and set the desired speed.
6. Once the desired speed is achieved, place the hopper in its intended place and pour the pellets inside it.
7. Manually grab the extruded filament and pass it through the holes on the cooling module.

8. Wait until the filament reaches the desired diameter.
9. Cut the filament up to this point.
10. Wrap the filament around a spooler.

4.0 Functional Testing and Results

4.1 Technical Specifications of the Extruder:

Weight	7-8kg
Power Consumption	220 VAC, Max 0.5 kilowatt/hour
Width	160mm
Length	410mm
Height	380mm
Nozzle Diameter	1.75mm

4.2 Experiment Conditions and Setup:

The setup for the different modules of the extrusion was established as shown in Fig. 12. The spool with the outer diameter of 20cm was used, and the distance between the center of the spool and the nozzle was 68cm. The cooler was placed at a distance of 18cm from the nozzle.

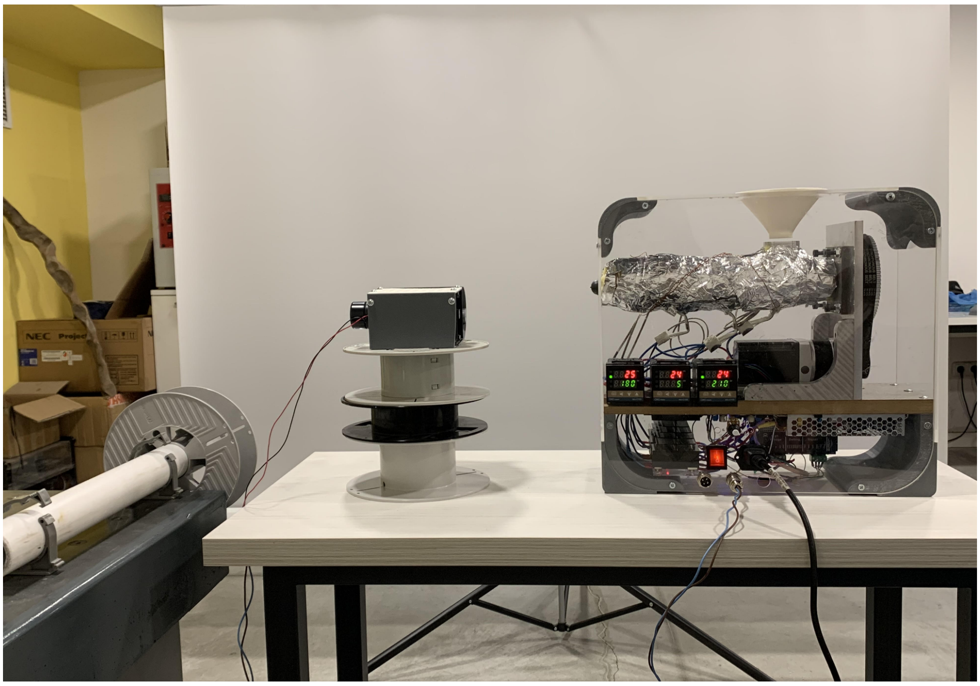

Fig. 12 The setup of the extrusion process

The experiments were conducted with recycled ABS plastic pellets shown in Fig. 13.

Fig. 13 Recycled ABS pellets that were used in the experiment

4.3 Test Cases:

Filament Quality Control Test:

The objective of this test is to obtain filament with high quality. The criteria for the quality of the filament was taken to be the presence of bubbles in the extruded filament. The evaluation process included the observation of bubbles in the filament, which were visible to the naked eye. Also, a tensile test was conducted to measure the level of ductility of the filament, which was affected by the number of bubbles in the filament; more bubbles lead to less ductility and more brittle filament.

Since the number of bubbles is directly influenced by the temperature values of the band heaters, the experiments were conducted by setting different temperature values using the heat controllers while keeping the other variables constant.

Based on research, ABS has a melting temperature of 200℃, and it is recommended to set the values of the heaters for extrusion purposes between 230℃-260℃. In order to achieve these values, as shown in Fig. 14, the sequentially increasing values of 221℃, 225℃, and 250℃ were set for the three heaters correspondingly.

Fig. 14 The initial setup of the temperature controllers

However, since the barrel is a heat conductor, the actual temperature value of the heater in the middle had a great margin with the set temperature value, causing the formation of bubbles in the filament as seen in Fig. 15.

Fig. 15 The low-quality filament with bubbles

In order to overcome this problem, the middle heater was set to a value below the room temperature, which means that the relay connected to the middle heater would be in normally open mode at all times and the heater would not heat up. The other two were also given a lower temperature in order to maintain an optimal temperature for the middle section of the extruder. The values of 210℃, 5℃, and 200℃ were given to the heaters, respectively. As can be seen in Fig. 16, the heaters settled at 210℃, 240℃, and 214℃, respectively.

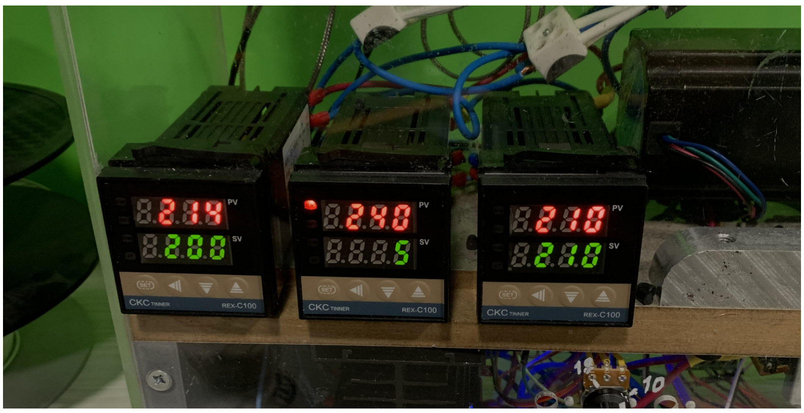

Fig. 16 The optimal temperature setup

As seen in Fig. 17, the quality of the filament improved drastically; there were no visible bubbles in the filament, and its ductility improved as well.

Fig. 17 The high-quality filament

The difference between the two obtained filaments is clear in the close-up image below (Fig.18).

Fig. 18 The low and high-quality filaments

One issue encountered when the temperatures were set as seen in Fig. 16 was that, when the number of pellets added to the barrel was increased, the pellets would partially melt and build up at the hopper base without moving forward. To overcome this issue, the temperature of the first heater which was set to 210℃, was changed to 170℃ which is lower than the melting point of ABS which is 200℃. However, in order to maintain a temperature inside the barrel that would be enough to melt the pellets, the value of the third heater was set to 210℃ (Fig. 19).

Fig. 19 Modified heater temperature

As the overall temperature inside the barrel had lowered compared to the previous instance, the speed of the screw was also lowered to 10 rpm in order for the pellets to have enough time to melt homogeneously. As seen in Fig. 20 the resulting filament was again of high quality, however with slightly more textured surface compared to the previous results. Therefore, the most optimal results were achieved with temperature values shown in Fig. 16.

Fig. 20 The slightly more textured filament

The difference between the high quality filament and the slightly textured one is more visible in the figure below (Fig.21).

Fig. 21 The slightly textured and high quality filaments

Filament Diameter Control Test:

The objective of the diameter control test is to attain a specific filament diameter range, enabling us to determine that a consistent 1.75mm diameter can be achieved once an automatic and constant speed puller is available. After establishing the optimal temperature values for having high-quality filament, the speed of the motor was set as a variable while keeping the temperatures of the heaters constant. The measurements were conducted by systematically varying the motor speed values, but the data was recorder for the two screw speed values which are 10 and 18 rpm as these values were observed to result in the high quality of the filament. For each speed, 20 data were recorded at 30-second intervals. The heaters were set at 210℃, 240℃, and 214℃, which are the optimal values obtained during the filament quality control test. Since the spooling was done manually, the speed of rotating the spool varied between 1.7 rpm - 2.2 rpm, which may affect the accuracy of the results. For the screw speed of 10 rpm, the resulting filament diameter range is 1.30 mm - 2.09 mm, and the average value of the 20 experiments is 1.597mm. For the screw speed of 18 rpm, the resulting filament diameter range is 1.43 mm - 2.01 mm, and the average value of the 20 experiments is 1.7265mm.

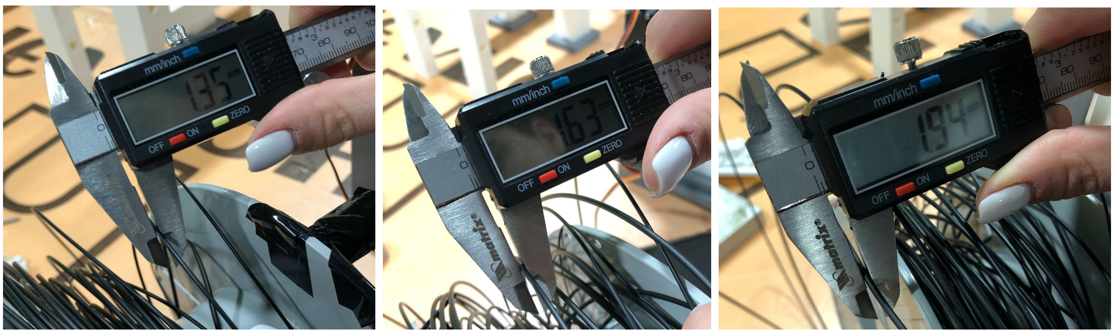

Fig. 22 Some of the results obtained during the experiment with 10 rpm screw speed

Fig. 23 Some of the results obtained during the experiment with 18 rpm screw speed

5.0 Performance Evaluation

The performance evaluation of the 3D printer filament recycler is a critical aspect of determining its success. The quality control test shows that the printer is able to produce a high-quality filament with no visible bubbles and improved ductility at the optimal temperature values of 210℃, 240℃, and 214℃. The filament diameter control test shows that the machine is able to produce a filament with an average diameter of 1.597mm for a screw speed of 10 rpm and 1.7265 for a screw speed of 18 rpm. Even though the average diameter value for the 18 rpm screw speed is close to the desired value of 1.75mm and does not exceed the accepted tolerance range of ±0.05mm, the manual rotation of the spool at different speeds might have had an impact on the accuracy of the results and diameter inconsistency. However, setting the acquired optimal temperature and speed values, the desired 1.75mm consistent diameter can be easily achieved using automatic puller.

The system can create high quality 3.14g/min of ABS filament with the optimal temperature values of 210℃, 240℃, and 214℃ and screw speed of 18rpm. Therefore, the ABS filament of 1kg can be achieved in 5.3 hours. The system power consumption is 0.5KWh, implying that 2.65kW will be consumed to have a filament of 1kg. The price per kilogram of the extruded filament was calculated based on the power consumption of the device (1kW = 50 AMD) and the calculated price is 133 AMD. Whereas, the price per kilogram of the ABS filament in local market is ~12.000 AMD. For the above-mentioned temperature values, the it takes the heaters 16-18 minutes to achieve the desired temperature, and with screw speed of 18 rpm, the filament starts extruding about 2 minutes after adding the pellets.

Overall, more data is required to accurately evaluate the performance of the 3D printer filament recycler device; however, the existing data show promising results for the time being, especially regarding the quality of the filament which was the main objective of this project.

6.0 Physical Environment

The system was assembled and tested at the AUA engineering laboratory. As the device needs to melt plastic materials and uses fiberglass as an insulating material, specific conditions should be maintained in order to avoid health risks and undesirable quality of the filament. Ventilation is a necessary condition for successfully implementing the extrusion. Moreover, adjusting the temperature and humidity in a well-ventilated space is simple. At the same time, it is vital to ensure the location of the device has adequate space between the walls and that air can flow through it. Covering the device should be avoided to guarantee air circulation between the electrical elements. The device must have enough room on all sides so that users can easily reach it and comfortably carry out regular maintenance duties. Additionally, it has to be situated on a sturdy surface that can withstand the vibrations produced by the device's usual operation.

7.0 Support Environment and Maintenance

Visual inspection of the components of the system should be conducted systematically in order to avoid further damage to the system. In addition, the system should be washed/cleaned after each usage to be sure that different types of plastic pellets do not get mixed. The user should remove the extruder and clear up any leftover material particles. Cleaning also can be done by using acetone for proper maintenance. After cleaning, checking whether the extruder is correctly fitted or not is essential. Moreover, extruders are functional components that eventually deteriorate with time due to wear and strain; hence, they might need to be replaced after some time. Moreover, it is essential to avoid overheating the motor and the motor driver.

8.0 Operational Scenarios, Use Cases, and/or Design Reference Missions

8.1 Nominal Conditions

In nominal conditions, first, if a shredder is available, the ABS-made material should be shredded and then dried to get rid of the moisture. If not, the pellets from already recycled ABS plastic should then be manually fed to the extrusion module through the hopper. Then the melting process of the pellets takes place inside the barrel of the extruder, after which the filament is forced out of the nozzle. Once the filament begins to extrude, it should be manually grabbed and led through the cooler module. The diameter of the filament should be checked either manually or using a diameter sensor at this step until the desired diameter is achieved. The filament produced up to this point is then removed, and the remaining part is manually wrapped around the spool.

8.2 Off-Nominal Conditions

In case of any accidents such as feeding the wrong material to the hopper, burning caused by touching the heaters or the barrel while the device is working, or any incidents with the screw, the pullers of other parts of the system, the user should immediately turn off the system using the On/Off button intended for it, which will immediately shut down the device and avoid further damage.

9.0 Impact Considerations

9.1 Environmental Impacts

This project targets the rising issue of plastic waste by making failed printed parts reusable through recycling. Since additive manufacturing (AM) offers more resource savings than conventional techniques, 3D printing can be viewed as a globally distributed manufacturing technology for enhancing sustainability and a circular economy. ABS and PLA are the two commonly used materials as filaments; hence the focus will be on the environmental impact of the recycling process of these two materials.

As a polymer made from plant starches, PLA is preferred because it is more environmentally friendly than filaments made from non-renewable resources (like ABS made from petroleum) and has the advantage of being recyclable. PLA filament releases lactide into the atmosphere when it is melted. But because it's a non-toxic substance, it's generally safe to be around. Compared to other 3D printing materials, PLA emits fewer VOCs and UFPs.

ABS, on the other hand, is not biodegradable. Furthermore, it is generally a more poisonous plastic than PLA; however, its recycling is more straightforward. Since ABS melts at higher temperatures than PLA, it emits higher VOC levels. Some VOCs are considered toxic for humans, and some can also contribute to the formation of ground-level ozone when reacting with NOx in the air. However, these issues are mainly observable in industrial settings. With a proper air ventilation system, the issues mentioned above can be avoided in domestic settings.

9.2 Organizational Impacts

This project does not require hiring a specialist who has experience in this field. It is easy to use this device, and it is also intended to be used by everyone interested in 3D printing and recycling. In labs or makerspaces, the specialist/engineer who utilizes 3D printers can use a 3D printer filament recycler device. The 3D printer filament recycler only requires knowledge of plastic types to avoid mixing different plastic types, their melting temperatures, and a basic understanding of the mechanism. The mechanism is similar to the 3D printer's and injection molding machine's mechanisms.

9.3 Scientific/Technical Impacts

Research into the production of biodegradable or compostable 3D printing filaments has thus far been primarily focused on attaining material printability, with little attention paid to material recycling or the entirety of the product life cycle. While focusing on the final goal of creating a device that will successfully recycle filaments, this project will also contribute to the broader field of plastic recycling and waste management.

10.0 Risks and Potential Issues

Functional Risks and Warnings:

- It is crucial to heat the plastic at the right temperature. Several heaters with different temperatures will provide constant and stable melting of the plastic. In case of wrong temperature values, the plastic pellets will be half-melted, which will stop the extrusion of the pellets, and the half-melted plastic will remain in the extrusion line, causing a need to clean the extruder and restart the process. In temperature experiments, hot plastic can reach a colder area of the screw (closer to the hopper) and solidify there, preventing the granules that have not yet melted from moving any farther.

- If plastic pellets are not dried properly, they might contain moisture which in turn will cause unwanted bubbles in the filament resulting in a bad-quality filament.
- If the extruder is not cleaned properly, then different types of plastic pellets might be mixed, and their melting temperatures will be different, resulting in a failure of the filament and the production of toxic gasses.
- If the device is on for a long period of time, make sure that the motor is not overheated and can function properly. If the motor is very hot, turn off the device or cool the motor with the fan.

Safety:

- Users should avoid turning the device on and off instantly as this might cause a failure in some of the electronic components. If the user turns the device off, it is recommended to wait several seconds or even a minute before turning the device on again.
- When the device is running, any interaction with the components of the device, except the interfaces, should be strictly avoided.
- As a fiberglass blanket is used as a thermal insulator on the extruder, the user should avoid touching the material with bare hands as it may cause allergic reactions.

11.0 Challenges Faced

There were a few challenges faced during both the assembling process and the experiments.

challenges faced during the assembly process:

- Frequent changes in the design of the frame of the extruder due to the addition of new elements, changes in the layout of the components, and structural issues.
- Issues with one of the heat controllers due to a loose wire connection.

challenges faced during the experiments:

- Spatial issues as the setup requires a large space.
- Improper air ventilation system in the lab, which caused the smell of the molten filament to remain in the lab for a long time, limiting the amount of time the experiments could be conducted.
- Inability to make an automatic puller module due to lack of time.

12.0 Future Works and Improvements

The 3D printer filament recycler is a working device with adequate results. The quality of the resulting filament can be further improved by:

- Adding an automatic puller module.
- Incorporating a diameter sensor and a PID controller inside the puller module to acquire real-time filament diameter values and change the pulling speed accordingly.

- Conducting more experiments to obtain more accurate data.
- Experimenting with different plastic types such as PLA.
- Adding an LCD to make the device more user-friendly.
- Adding pre-defined modes based on the optimal results acquired from a sufficient amount of experiments.

Appendix A: Acronyms

Acronym	Meaning
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
NOx	Nitrogen Oxides
PLA	Polylactic Acid
UFP	Ultrafine Particles
VOC	Volatile Organic Compounds

Appendix B: Glossary of Terms

Term	Definition
ABS	one of the most common thermoplastics for 3D printing
Additive Manufacturing	a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers
Auger	a device consisting of a shaft with a broad helical flange rotating within a cylindrical casing to force bulk materials from one end to the other.
Barrel	a hollow chamber in which the screw operates
Circular Economy	a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling
Extruder	a machine that extrudes material (plastic in this case) through shaped dies
Filament	material used to form the printed object

Frugal engineering	Frugal engineering concerns the systematic creation of products that are low in cost, consume lesser resources and give good functionality
Ground-level ozone	a colorless and highly irritating gas that forms just above the earth's surface which is harmful for human health.
Hopper	funnel-shaped receptacle for delivering material
Makerspace	a place in which people with shared interests, especially in computing or technology, can gather to work on projects while sharing ideas, equipment, and knowledge
Module	a distinct assembly of components that can be easily added, removed or replaced in a larger system
Pellet	small granules of plastic
PLA	a thermoplastic monomer derived from renewable, organic sources such as corn starch or sugar cane
VOC	gasses that are emitted into the air from products or processes