ADVANCED PET PLASTIC BOTTLE UPCYCLING FOR PRECISION 3D PRINTER FILAMENT FABRICATION

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Abstract: *This scientific article introduces the PET-Machine, a prototype aimed at transforming recycled PET plastic bottles into high-quality 3D printer filament. The article outlines the prototype's design, engineering, and operational principles, highlighting its potential to contribute to sustainable additive manufacturing. The PET-Machine prototype integrates a comprehensive process, from bottle collection and material purification to polymer extrusion, resulting in filament suitable for precision 3D printing. Through rigorous filament characterization, including mechanical property analyses and compatibility assessments, the prototype's practicality and compatibility with existing 3D printing systems are demonstrated. The PET-Machine prototype offers a practical solution for plastic waste upcycling while aligning with eco-conscious manufacturing practices. This machine represents a step towards a more sustainable future in additive manufacturing.*

Keywords: *PET-Machine prototype, 3D printer filament, Recycled PET, Environmental impact.*

1. Introduction

The global issue of plastic waste has reached alarming proportions, necessitating innovative solutions to address its environmental impact. This scientific article presents a groundbreaking development in the realm of sustainable additive manufacturing: the PET-Machine. This prototype, meticulously designed and engineered, aims to improve the utilization of recycled PET plastic bottles by transforming them into high-quality 3D printer filament. The PET-Machine embodies a comprehensive process that encompasses bottle collection, and polymer extrusion, ultimately yielding filament suitable for precision 3D printing. This article delves into the intricacies of the prototype's design and operational principles, shedding light on its potential to significantly contribute to sustainable manufacturing practices.

In the context of a burgeoning 3D printing industry and increasing concern about plastic pollution, the PET-Machine emerges as a beacon of hope. Through rigorous filament characterization, including mechanical property analyses and compatibility assessments with existing 3D printing systems, this article demonstrates the practicality and viability of the PET-Machine. By providing a practical solution for plastic waste upcycling, the PET-Machine aligns with the imperative of eco-conscious manufacturing, paving the way for a more sustainable future in additive manufacturing. This machine represents a pivotal step toward addressing the environmental challenges posed by plastic waste, all while advancing the possibilities of 3D printing technology.

2. Prototype development

The proposed system aims to transform pet into a 1.75mm filament using a 3D printer nozzle. The process is automated through a "Nema 17" stepper motor [1], pulling the filament at a constant and reduced speed to ensure its uniformity and homogeneity. Speed control is achieved through geared wheels and an HY-DIV268N-5A motor driver [2]. Maintaining a moderate speed is essential to

avoid gaps in the filament and prevent exceeding the melting temperature of PET, which could lead to bubble formation. The process details are presented in a schematic diagram, and the necessary materials and components are listed in an Excel file.

2.1. 3D Design

In the 3D design project, components such as the couple system made through geared wheels and the PET support with the pet cutting knife were created in Solidworks program (fig.1). The objective is to achieve a constant cross-sectional area, regardless of the thickness of the pet, by adapting the strip's height.
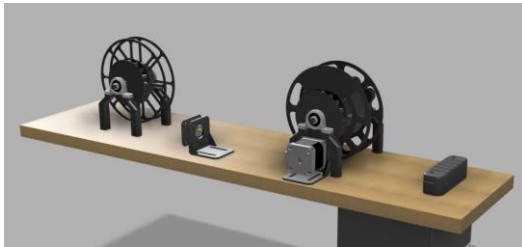

Figure 1: *The initial designed components.*

2.2. Temperature Control and Filament Production: From Scheme to PCB

An electronic scheme was developed for temperature control, including start circuits, signal filters, pins for serial communication with the LCD, encoder [3], and motor driver. It was later mounted on a PCB with an ATMEGA328P [4], [5], [6]. microcontroller. The project benefited from using the EasyEDA program for scheme and PCB design. The microcontroller integrates analog-to-digital converters for temperature measurement and Hall sensors for checking the circular section of the filament. An NTC thermistor is used for temperature measurement, and an RC [7] low-pass filter is implemented to eliminate noise at the microcontroller input. The microcontroller is powered from a 5V source, and an external oscillator connected to XTAL1 and XTAL2 sets the sampling speed to 16MHz. Printer nozzle power is supplied through a switch and an N-type IRF field-effect transistor [8], [9],

[10]. Ports for external components such as the encoder, stepper motor, and LCD display have been integrated. PCB design pays careful attention to aspects such as minimizing disturbances, protecting traces under voltages higher than 5V, and avoiding 90-degree angles, with exceptions at the connection points between 3 traces. A 3D model of the PCB was created to provide a visual perspective on its real appearance (fig.2).
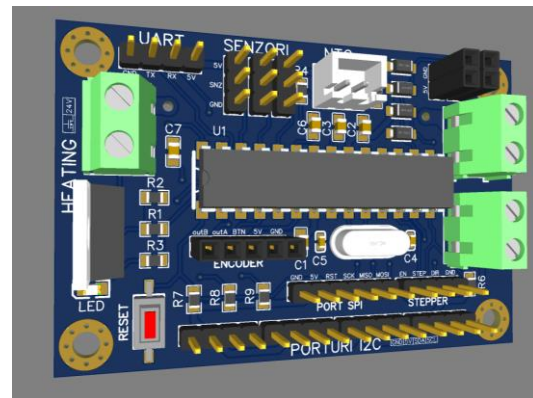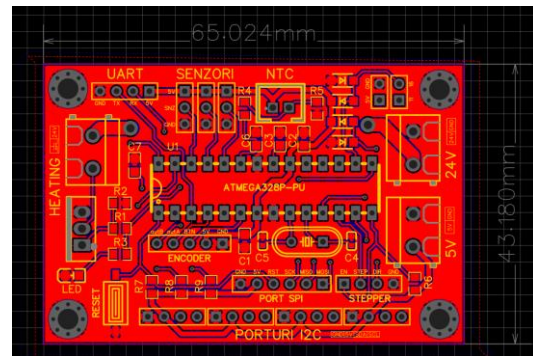

Figure 2: *The PCB layout in EasyEDA.*

2.3 Precise Control of NEMA 17 Stepper Motor with Arduino Board: From Programming to Implementation

The NEMA 17 stepper motor underwent tests using an Arduino board, with microcontroller programming done in embedded C. The Arduino code was translated into embedded C using Platformio. In the initial stages, a motor command was implemented to adjust the speed based on the value read from an encoder. The motor was connected to a HY-DIV268N-5A driver (fig.3), powered at 24V, allowing the current value to be adjusted to increase the motor's

torque and step. The operating limits of the motor, such as a maximum current of 3.5A and a continuous current of 1.8A, were considered. The command was adjusted to use an AccelStepper library [11] and allow LCD-motor-microcontroller communication, addressing initial issues.

Figure 3: *The driver model used.*

2.4. User Interface: LCD Menus for Temperature and Motor Speed Setting

The development of a user interface for LCD was initiated (fig.4), allowing the adjustment of nozzle temperature and stepper motor speed. The motor has bidirectional rotation to extract the pet ribbon and transform it into filament by passing through the nozzle. The menus display the project name, and the first functional menu offers the option to create a ribbon or filament, each with its sub-menus for setting speed and temperature. The simulation of the display operation was done using the Wokwi website, presenting the schematic and startup screens, as well as the menus for ribbon and filament. The displayed values can be modified through the encoder. A notable feature of the display is the ability to define special characters, and the user can create up to 8 such characters. Characters for the startup screen were defined. Each box inside the LCD can contain a character defined by an 8x5 matrix, and defining these characters involves knowing the hexadecimal value that activates or deactivates the LEDs in each line. The recognized address of the LCD for a specific character is 0x1A. The total number of defined characters must be equal to the number of lines in the LED matrix.

Defining these vectors is essential, given the limited number of characters that can be displayed simultaneously on the screen.
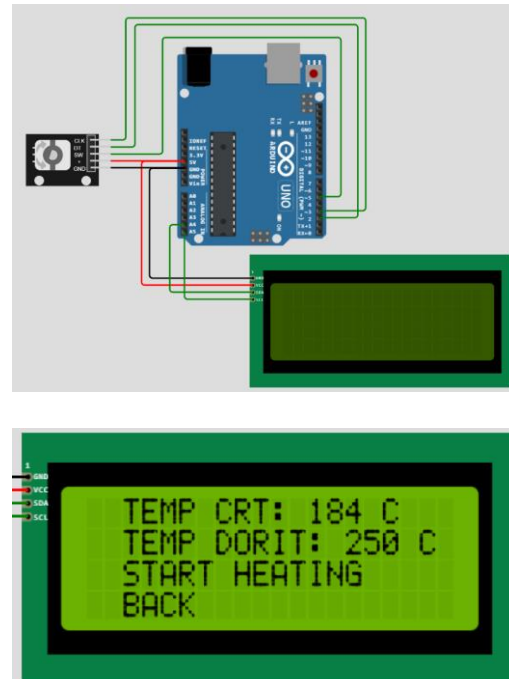

Figure 4: *Schematic and temperature selection menu.*

2.5. Precise Temperature Adjustment with PID Controller: Tests and Optimization for Filament Production

Testing the temperature control was initiated by programming a PID controller to regulate the nozzle temperature within set limits. A formula was developed that links the displayed temperature value from the thermistor to the analog-to-digital converter reading, with a reference of 5V. The thermistor was characterized by a resistance value at 25 °C and a specific material coefficient (β) of 3950 K.

$$R_1 = R_0 e^{\beta(T_1^{-1} - T_0^{-1})} \tag{1}$$

$$U_{OUT} = U_{REF} \frac{R_1}{R_1 + R_2} \tag{2}$$

A mathematical model was developed to correlate these variables and obtain a reading in the range of 0-1023, depending on the temperature. Tests included comparing calculated values for the thermistor resistance

with a table and creating graphs in MATLAB for precision. The formula was tested and calibrated to ensure an error of no more than 2 °C. Tests were successfully conducted for both pull-up and pull-down configurations of the R2 resistor. Subsequently, an attempt was made to pull a filament from PET ribbons using a nozzle powered at 12V and imposing a temperature of 260 °C in the PID code. The temperature scanner indicated a lower temperature than that read by the thermistor, and this discrepancy can be attributed to the fact that the reading is done inside the thermistor, while the nozzle reaches higher temperatures (fig.5).
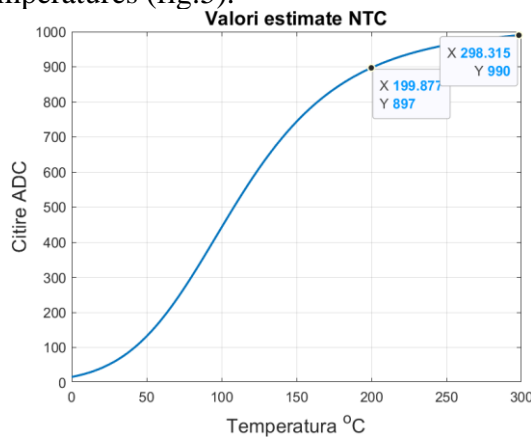

Figure 5: *The temperature graph with expressed values.*

2.6. PCB Assembly and Integration: Unifying Codes for Seamless Functionality

Ordered PCBs arrived, along with corresponding electronic components. The assembly of the entire system began by mounting the components on the PCB. Different codes for the motor, LCD display [12], and PID regulator [13], [14], [15], [16]. were integrated into a single program for the microcontroller. The LCD code was optimized to eliminate flicker on the menu arrow and allow modification of displayed values, including the desired nozzle temperature and motor rotation speed as a percentage. A special function from the AccelStepper library was implemented to impose a maximum speed expressed as a percentage, and when the maximum number of steps was reached, the displayed percentage is 100%. The PID regulator code occupied a significant part of

the memory due to the vector used for temperature calculation, affecting LCD functionality. This issue was resolved by transferring the vector to the microcontroller's Flash memory. The syntax was modified to allow calling the vector and performing temperature calculations. Subsequently, adjustments were made to start filament production. The way the nozzle was mounted acted as a radiator, requiring a temperature command of over 400 °C to produce filament. The tip of a PET ribbon was cut, and an attempt was made to pull it through the nozzle to obtain filament. The process was successful, with a constant diameter of 1.5 mm, although the standard is 1.75 or 1.8 mm. The diameter of the ordered nozzles was 0.4 mm, and to increase them, a drill was used, obtaining the corresponding diameter.

2.7. Innovative Solutions for Thermal and Couple Issues in Filament Production

Two solutions were proposed to compensate for the radiator's effect on nozzle heating. The first solution involves replacing the metal vise with a thermal insulating material or fixing the nozzle in the vise with that material. The second solution consists of modifying the mathematics in the code so that for a desired temperature value, the transmitted command is higher than normal, and the thermistor indicates a lower temperature than the actual one. By increasing the desired temperature value in intervals of 20 °C, a final result was obtained, showing a gradual increase in the ratio between the desired and current temperatures, as well as the ratio between the desired and scanner-taken temperatures.
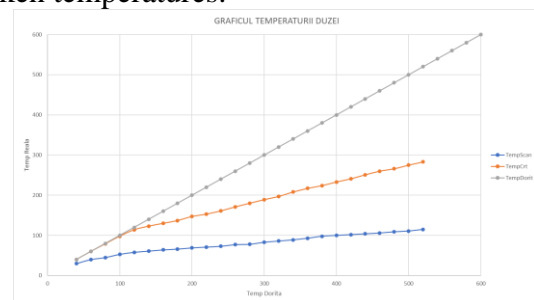

Figure 6: *The nozzle temperature graph.*

The temperature indicated by the thermistor is higher than that of the nozzle, and the nozzle tip heats up more slowly than the thermistor (fig.6). Another identified problem is related to the torque development by the stepper motor, which is not large enough to produce the filament ribbon. To solve this problem, the proposal is to create a transmission with the highest possible transmission ratio (fig.7). This ratio is calculated based on the number of teeth of the wheels involved in the transmission and can be optimized by adjusting their values (Z1, Z2, Z3, Z4). Choosing small values for Z1 and Z3 contributes to obtaining a higher torque.
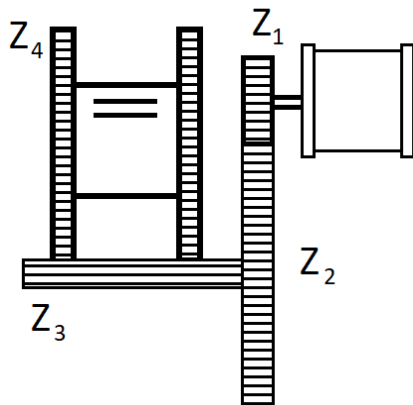

Figure 7: *The kinematic diagram for the motor torque.*

2.8. Testing and System Optimization

In this stage of the project, the transmission was 3D printed, assembled, and subjected to rigorous tests to evaluate the system's performance in subsequent filament pulls. Although the motor and transmission system produced a considerable level of noise, we managed to achieve sufficient torque to ensure efficient filament pulling. In an attempt to minimize the generated noise, spacers were implemented to eliminate play between parts, and silicone parts were added to the stepper motor to absorb vibrations and reduce emitted noise. However, we faced initial difficulties due to high friction generated between the cutter walls and the cut ribbon, resulting in a significant noise level. To overcome this problem, we opted for an innovative solution,

introducing two bearings with cut and ground edges in the cutter configuration. This optimization of the cutter configuration had a significant impact, significantly reducing the noise associated with the ribbon cutting process.

After completing this stage, I observed that the system can successfully handle a pet with a thin wall of 0.2 - 0.3 mm, pulling it through the printer nozzle. This result indicates efficient optimization of the system, preparing it to produce complex parts on a 3D printer capable of pulling ribbons with thicknesses of up to 8 mm.

In parallel with these improvements to the traction system, I intervened in the PID control of the nozzle temperature (fig.8) to correct shortcomings identified in the extruder's operation. Adjustments included a fundamental change to the PID, where the constant transmission of "h" command data required the use of timers integrated into the ATMEGA328 microcontroller. These timers allowed efficient and separate data transmission to the motor, PID, and managed crucial interruptions for the LCD display. The microcontroller, equipped with 3 built-in timers, was programmed at the register level to configure the signal generation module and clock selection for PWM control [17], [18]. The CTC operating mode was preferred, with a clock frequency divided by 256 for the motor and 1024 for the PID.

$$f_{OC_{nx}} = \frac{f_{clk}}{2 \cdot N \cdot (1 + OCR_{nx})} \qquad (3)$$

I implemented OCRA registration to impose PWM frequency values, calculating them based on the settings in the register (f_{clk} is the microcontroller frequency, which in our case is 16 MHz, imposes a maximum frequency at $OCR_{nx} = 50$, so $f_{OC_{nx}}$ is approximately 610 Hz; the N variable represents the prescale factor).
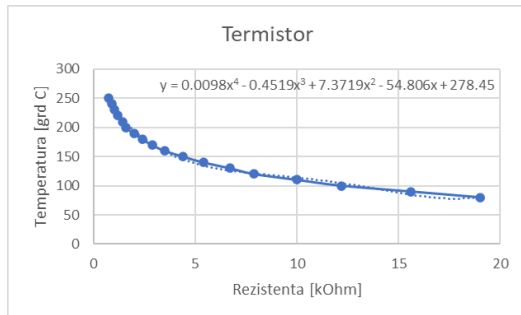
Figure 8: *The graph with temperature calculation based on voltage.*

Regarding the PID aspect, we rewrote the algorithm using a new library, with adjusted k_p, k_i, k_d constants, and the nozzle holding mode was modified to improve thermal efficiency. To align the correct operation of the motor and PID while using the LCD display, I implemented interruptions on Timer2.

These significant improvements to the system contributed to more efficient operation and achieving the desired results in the pet recycling filament production project.

3. Results and Discussions

Figure 9: *The final model of the PET-Machine.*

Exploring alternative materials for the thermal insulator could enhance the system's efficiency. Investigating materials with superior insulating properties or designing a modular insulator system that allows for easy replacement and experimentation can contribute to better temperature control and overall performance.

The PID algorithm, while effective, can undergo continuous refinement for even more precise temperature control (fig.9). Fine-tuning the PID constants, exploring adaptive PID algorithms, or incorporating machine learning techniques to dynamically adjust control parameters based on real-time feedback could lead to optimal temperature profiles and further stabilize filament production.

The design and material composition of the nozzle play a crucial role in filament production. Future iterations of the project could involve exploring different nozzle geometries and materials to optimize the extrusion process. Investigating nozzles with varying diameters and surface treatments may contribute to achieving the desired filament diameter and quality.

Incorporating smart sensors for real-time monitoring of key parameters, such as filament diameter and temperature gradients, can enhance the system's responsiveness. Advanced sensors could provide valuable data for adaptive control strategies, allowing the system to dynamically adjust parameters based on the specific characteristics of the recycled pet being processed.

As sustainability is a key focus of the project, future developments could explore ways to further reduce energy consumption and waste. Investigating energy-efficient heating methods, such as induction heating, or incorporating additional recycling features for unused filament material could align the system with more eco-friendly practices.

Implementing machine vision technology for real-time monitoring of the filament production process can offer precise quality control. Vision systems can detect imperfections, irregularities, or variations in filament diameter, enabling immediate adjustments and ensuring consistent and high-quality filament output.

Collaborating with recycling initiatives and organizations could provide valuable insights and resources for sourcing recycled pet. Establishing partnerships with entities dedicated to sustainable practices can ensure a steady and environmentally conscious supply of raw materials for the filament production process.

Continued efforts can be directed towards making the system more accessible and user-friendly. Streamlining the user interface, developing detailed user manuals, and incorporating remote monitoring and control features can enhance the overall user experience and facilitate broader adoption of the technology.

In summary, the future directions and improvements outlined above present a roadmap for the ongoing development of the pet to filament transformation system.

Continuous innovation and refinement in these areas will contribute to the project's long-term success and further establish its position as a sustainable and advanced solution in the field of additive manufacturing.

4. Conclusion

In conclusion, our journey to innovate pet-to-filament transformation through an advanced 3D printing system has culminated in significant achievements and promising avenues for further development.

The automated system's success in transforming pet into a 1.5mm filament, despite a slightly substandard diameter, underscores its potential for optimization. The precision achieved in temperature control, facilitated by a robust PID algorithm, has laid the foundation for consistent and reliable filament production.

The user interface, featuring LCD menus and interactive controls, adds a layer of sophistication to the system, enhancing user experience and control. The integration of machine vision and smart sensors in future iterations promises to elevate the system's capabilities in real-time quality control and responsiveness.

The mechanical design, including 3D-printed components and innovative solutions to address noise and friction issues, reflects the feasibility and adaptability of our approach. The successful 3D printing of transmission components and the utilization of bearings for noise reduction showcase the potential for scalable and sustainable manufacturing.

Challenges encountered, such as the radiator effect and torque limitations, have sparked creative solutions and paved the way for future enhancements. Proposals for alternative thermal insulators, continuous PID algorithm refinement, and exploration of nozzle design variations promise to address these challenges and further optimize the system.

The integration of sustainable practices, such as collaboration with recycling initiatives for a steady supply of recycled pet, aligns with our commitment to eco-friendly 3D printing solutions. Future endeavors will focus on minimizing energy consumption and exploring additional recycling features.

In the testing and optimization phase, the system demonstrated its capability to handle thin-walled pet efficiently, setting the stage for the production of intricate 3D-printed parts. The reduction of noise through innovative solutions and the successful application of bearings in the cutter configuration mark milestones in achieving a quieter and more efficient production process.

As we conclude this phase of the project, the system stands poised at the forefront of pet recycling filament production. Ongoing efforts will center on refining and expanding the system's capabilities, with a keen eye on sustainability, precision, and user-friendly operation. Our innovation in pet-to-filament transformation opens doors to a new era of eco-conscious 3D printing, positioning our project as a pioneering force in the realm of advanced manufacturing.

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