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Author: Ismael Andrés Paredes Bustamante

Tutor: Vladimir Félix Bonilla Venegas

Diseño y construcción de un sistema de extrusión para el reciclaje de granulados de impresión 3D (PLA y PETG).

Design and Construction of a Extrusion System
for 3D Printing Flakes Recycling (PLA and PETG).

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Aprobación del Tutor del Trabajo de Integración Curricular

Yo Vladimir Félix Bonilla Venegas, en calidad de tutor del Trabajo de Integración Curricular denominado: *Diseño y construcción de un sistema de extrusión para el reciclaje de granulados de impresión 3D (PLA y PETG)*., realizado por Ismael Andrés Paredes Bustamante, ha sido orientado y revisado en todas sus partes y considero que cumple los requisitos establecidos por la institución. En virtud de ello doy mi aprobación a fin de continuar con el proceso académico correspondiente.



Validar únicamente en FirmaEC.
Firmado electrónicamente por:
**FELIX VLADIMIR
BONILLA VENEGAS**

Vladimir Félix Bonilla Venegas

Tutor del Trabajo de Integración Curricular

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Autor: Ismael Andrés Paredes Bustamante

C.I.: 1722107552

Dedicatoria

Quiero dedicar este trabajo a mis padres por ser mi apoyo incondicional en cada etapa de este largo camino. Gracias por enseñarme el valor del esfuerzo, por creer en mí cuando yo dudaba de mis capacidades y por acompañarme con paciencia y amor. Cada logro que alcanzo lleva su sacrificio y es fruto de sus enseñanzas y su ejemplo. No hay palabras suficientes para agradecer todo lo que han hecho por mí. Siempre llevaré conmigo y con mucho orgullo todo lo que me dieron: valores, fuerza y corazón. A mi madre por siempre estar ahí y a pesar de no entender mucho de lo que le contaba, siempre me dió ánimos para seguir adelante y siempre intentar ser el mejor. A mi padre por siempre apoyarme con ideas para proyectos, en formas de realizar las cosas y por la motivación que me ha dado para sacar a flote todos mis objetivos.

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Resumen

El trabajo realizado presenta el diseño, construcción y validación de un sistema de extrusión para el reciclaje de residuos de impresión 3D FDM. Esta máquina está enfocada en volver filamento a restos de impresiones de PLA. La metodología seguida en este trabajo fue la basada en el modelo en V de la norma VDI 2206, esta describe el uso de cálculo analítico, simulación por elementos finitos y prototipado iterativo en base a falencias encontradas. Se dimensionó un tornillo de extrusión de 18mm de diámetro con una relación de compresión de 3:1. Este es accionado por un motor a pasos NEMA 23 con una caja reductora de 15.3:1, dando un factor de seguridad de 2.39 para asegurar el cizallamiento dentro del barril extrusor. Además, un subsistema de rebobinado fue implementado para el uso posterior del filamento reciclado. El procesamiento está hecho con un microcontrolador ESP32 que se encarga del procesamiento de PIDs, control de velocidades de motores y retroalimentación del sensor de diámetro de filamento. Para el manejo del sistema, se diseñó una interfaz hombre-máquina que ofrece varios menús de configuraciones e información de la cual se encarga un microcontrolador Arduino Nano. Se implementó un control térmico a través de tres lazos PID independientes para asegurar la distribución térmica en el barril, logrando errores en estado estacionario menores o iguales a 2°C. Entre ambos microcontroladores se comunican por el protocolo UART para que no exista una pérdida de información y el sistema funcione correctamente. Las pruebas de extrusión se realizaron con una mezcla 60/40 de PLA virgen y reciclado y produjeron filamento continuo alcanzando un diámetro promedio de 1.18 mm a 6 RPM, sin lograr el objetivo de 1.75 mm de filamentos comerciales. El prototipo demostró viabilidad operacional, pero requiere de optimización del perfil térmico y coordinación de velocidades.

Palabras clave: control PID, extrusión de filamento, manufactura aditiva, mecatrónica, reciclaje.

Abstract

The work carried out presents the design, construction and validation of an extrusion system for the recycling of FDM 3D printing waste. This machine is focused on turning PLA print scraps into printable filament. The methodology followed in this work was based on the V-model of the VDI 2206 standard, which describes the use of analytical calculus, finite element simulation and iterative prototyping based on deficiencies found. An 18mm diameter extrusion screw with a compression ratio of 3:1 was dimensioned. This is driven by a NEMA 23 stepper motor with a 15.3:1 gearbox, giving a safety factor of 2.39 to ensure shear forces inside the extruder barrel. In addition, a rewinding subsystem was implemented for the subsequent use of the recycled filament. The processing is done with an ESP32 microcontroller that takes care of PID processing, motor speed control, and filament diameter sensor feedback. To operate the system, a human-machine interface was designed that offers several menus of settings and information that is handled by an Arduino Nano microcontroller. Thermal control was implemented through three independent PID loops to ensure thermal distribution in the barrel, achieving steady-state errors less than or equal to 2°C. Between both microcontrollers, they communicate by the UART protocol so that there is no loss of information and the system works correctly. Extrusion tests were performed with a 60/40 mixture of virgin and recycled PLA and produced continuous filament reaching an average diameter of 1.18 mm at 6 RPM, without achieving the target of 1.75 mm of commercial filaments. The prototype demonstrated operational feasibility, but requires optimization of the thermal profile and coordination of speeds.

Keywords: additive manufacturing, filament extrusion, mechatronics, PID control, recycling.

ABET Criteria/Final Report Cross Reference Table

ABET Criterion Outcome	Target Level of Mastery	Best Examples with Section Numbers
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Analysis, Synthesis	Sections 2.4, 2.4.1, 2.4.2, 2.4.4
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Synthesis, Evaluation	Sections 1.1, 2.2, 2.3
3. An ability to communicate effectively with a range of audiences.	Synthesis	Sections 2.4.5, 3.1.4, 4.2
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Evaluation	Sections 1.1, 4.1
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Synthesis	Sections 2.1, 2.2
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Analysis, Evaluation	Sections 2.4.8, 3.1.2, 3.1.5, 3.2
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	Analysis, Synthesis	Sections 1.1, 2.1, 2.4.3

Chapter I

Introduction

The rapid expansion of Additive Manufacturing, particularly of the Fused Deposition Modeling (FDM), has significantly transformed prototyping, education, and decentralized manufacturing due to its easy accessibility, low cost, and material versatility. However, the increasing use of this technology has also augmented the generation of waste derived from failed prints, support structures, calibration attempts, and discarded iterations [1, 2]. Although because of the nature of these materials, the accumulation of them represents an important concern regarding the environmental perspective due to their lack of biological decomposition in nature. To overcome this problematic, the transition to a circular economy models in this type of manufacturing has become more important so strategies where this type of waste is recovered, processed and transformed into reusable material rather than discarding it [3].

Between some strategies, distributed recycling appeared as an important alternative allowing for in-situ recycling by shredding, thermal processing, and filament re-extrusion directly at the point of consumption that can be for self-use or a small commercial use. Previous studies showed that distributed recycling systems can significantly reduce environmental impact compared to centralized recycling infrastructures by minimizing transportation costs (monetary and environmental), reducing energy-intensive sorting stages, and improving material traceability within small-scale production environments [4, 5]. Also, the on-site recycling of waste into printable filament represents an economically attractive solution for educational institutions and laboratories, where there is an important accumulation of failed prototypes and discarded prints [6].

Despite the environmental and economic advantages of localized filament production, the implementation of small-scale extrusion systems presents significant technical challenges that have to do with plastic processing, thermal stability, and machine design. Most desktop filament extruders depend on single-screw extrusion mechanisms, in which the final filament quality strongly depends on the interaction between screw geometry, thermal regulation, material feeding conditions, and pulling speed synchronization [7, 8].

In this context, recycled thermoplastics such as Polylactic Acid (PLA) and Polyethylene Terephthalate Glycol (PETG), most known and used materials in FDM printing, present

complex thermomechanical behavior during their processing. Repeated extrusion cycles may induce progressive degradation mechanisms in PLA, including molecular chain scission and alterations in rheological properties, which can compromise its performance, dimensional stability, and interlayer adhesion in printed components [6, 9–11]. Despite this analysis, previous experimental studies demonstrated that blending recycled PLA with controlled proportions of virgin material partially restores mechanical performance and stabilizes extrusion behavior, suggesting viable strategies for improving recycled filament quality [12, 13].

Similarly, PETG processing introduces more challenges because of its sensitivity to moisture absorption and elevated processing temperatures. During extrusion, residual humidity trapped within the polymer trigger hydrolytic degradation, vapor bubble formation, and internal porosity, this affecting the filament continuity and dimensional consistency if a well preprocessing step is not applied before working with it [14–16]. Consequently, maintaining controlled thermal gradients and stable polymer flow throughout the extrusion process becomes essential to minimize degradation while preserving material integrity [17, 18]. Since polymer transport and melting inside extrusion systems are controlled by pressure generation, shear heating, residence time, and progressive channel compression, the proper thermomechanical sizing of the extrusion assembly represents a critical requirement for achieving continuous and stable material flow [19–21].

However, despite the growing body of research on recycled thermoplastics and localized manufacturing, an important engineering gap persists in the formal design and validation of desktop-scale filament extrusion systems. There is a significant number of existing open-source extruders that have been developed empirically or adapted from non-specialized mechanical assemblies without rigorous engineering justification regarding screw geometry, torque requirements, structural resistance, or thermal management [7, 21]. In many cases, the absence of mathematically derived compression ratios, shear estimations, and thermal zoning strategies limits extrusion consistency and compromises filament quality, particularly when processing recycled flakes with irregular geometries and a variation in their densities.

Contrary to standardized industrial pellets, shredded plastic particles usually trap significant volumes of air during feeding, generating unstable material transport and pressure fluctuations inside the extrusion channel. When screw geometries lack an adequate compression and transition stage to progressively densify material and remove this trapped air, these discontinuities may propagate toward the nozzle, producing inconsistent flow, filament porosity, and

dimensional instability [19,20]. Additionally, horizontal feeding architectures commonly experience irregular material intake due to poor gravitational assistance when lightweight flakes are processed, increasing the probability of clogging or extrusion interruptions. These limitations demonstrate the necessity of a more specific mechatronic approach capable of integrating mechanical sizing, thermal control, structural verification, and stable feeding mechanisms into a single coordinated system.

In order to overcome these identified challenges, the current research work proposes the design, construction, and validation of a vertical single-screw mechatronic extruder for the recycling of PLA and PETG waste into reused filament for 3D printing. A vertical architecture was used to improve feeding taking advantage of gravitation for the material transport, trying to reduce flow interruptions because of irregular shredded flakes. At the same time, the system was designed to incorporate a multi-zone thermal control strategy to improve temperature uniformity throughout the barrel and a high-torque powertrain designed to handle efficiently the high viscous resistance associated with molten recycled plastics. Unlike empirical desktop extrusion systems, the proposed machine integrates thermomechanical calculations, finite element analysis, thermal simulation, and electronic control strategies to establish a more specific engineering framework for desktop extruders. The primary objective of this research is to develop a technically robust and economically accessible extrusion system capable of transforming thermoplastic waste into filament with dimensional consistency suitable for FDM printing. Specifically, the study seeks to perform the thermomechanical sizing of the extrusion assembly, develop an adequate powertrain for high-viscosity materials, implement an electronic control system for thermal regulation and process monitoring, and experimentally validate the operational feasibility of the proposed system.

Chapter II

Methodology & Design

2.1 Research Methodology

An applied and experimental engineering methodology was applied in this research work with a quantitative approach to developing a mechatronic extrusion system accomplishing the objective of recycling thermoplastic waste into usable 3D printing filament. The study focused on the integration of mechanical, thermal, electrical, and control subsystems into a single functional system designed to process shredded PLA and PETG waste under controlled operating conditions.

The development process required a structured methodology capable of synchronizing the interactions between the mechanical structure, thermal energy transfer, electronic control, and material transport processes due to the requirements to ensure the correct working of the system. For this reason, the followed design methodology was the VDI 2206 for mechatronic systems which provides a systematic framework for interdisciplinary product development. Combining the methodology with analytical modeling, numerical simulation, and iterative prototyping worked to progressively validate design hypotheses before final implementation. To estimate the mechanical power requirements, material transport rate and extrusion capacity, mathematical calculation and estimations were applied. In addition, a finite element analysis (FEA) and thermal simulations were configured to evaluate the structural behavior of components and thermal distribution in the extrusion barrel in a virtual validation phase before construction.

To reduce manufacturing risks and economic costs associated with custom machining, a progressive prototyping strategy was adopted. Intermediate assemblies were experimentally built to validate the feasibility of the system's powertrain, thermal architecture and extrusion principles. This approach allowed a step-by-step refinement of the complete system minimizing design errors. Finally, the methodology was designed to establish traceability between the initial stakeholder requirements and the final mechatronic implementation, ensuring that each subsystem satisfy the functional, non-functional and constraints defined during the early stages of the project.

2.2 Mechatronic Design Methodology Based on VDI 2206

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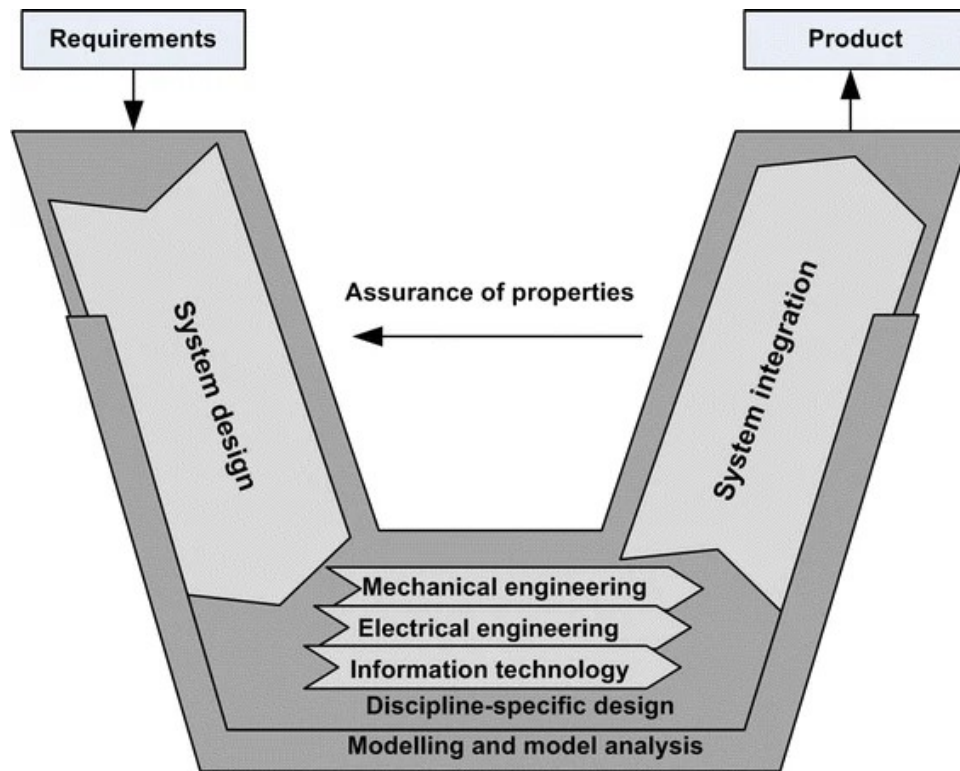


Fig. 1. Application of the VDI 2206 V-model methodology to the development of the mechatronic extrusion system [22].

As mentioned, analytical modeling and simulation were done, for these tools were employed throughout the development process to reduce uncertainty before fabrication. Structural analyses were done using Autodesk Inventor 2025 to evaluate the mechanical integrity of load-bearing components, while thermal simulations were performed in SolidWorks 2024 to analyze temperature propagation and thermal uniformity along the heating barrel. This methodology allowed a systematic transition from abstract requirements to a manufacturable solution while reducing technical risks associated with mechanical failure, thermal instability, and subsystem incompatibilities.

2.3 System Requirements

The initial phase of the design process was directed toward translating stakeholder needs into quantifiable engineering requirements to guide the development of the mechatronic extrusion system. The requirements definition took into account functional performance, operational usability, safety, manufacturing feasibility and economic constraints, as the machine was intended for localized thermoplastic recycling in an academic laboratory environment. System requirements were classified into functional requirements, non-functional requirements and project constraints to allow a clear engineering traceability.

2.3.1 Functional Requirements

Functional requirements describe the essential operational capabilities that the system must satisfy to accomplish its designed objective. These requirements were primarily related to material transport, thermal processing, motion generation, and filament production quality. The extrusion system was required to process shredded PLA and PETG flakes, extrude the material under controlled temperatures, generate sufficient mechanical torque to maintain continuous extrusion, and produce filament with a target diameter compatible with commercial FDM printers. Table 1 summarizes the functional requirements established during the initial design phase.

TABLE 1
Functional Requirements of the Mechatronic Extrusion System.

ID	Requirement Description	Target Operational Value
RF1	Material Processing	Accept and compress shredded PLA or PETG flakes with a 3:1 compression ratio
RF2	Thermal Control	Independent PID regulation up to 190°C (PLA) and 240°C (PETG)
RF3	Motion Actuation	Provide at least 6.48 Nm of operating torque at 20 RPM, with a mechanical safety factor greater than 2
RF4	Output Geometry	Continuously extrude filament with a target diameter of 1.75 ± 0.05 mm

These functional requirements established the technical capabilities that the machine needs to satisfy.

2.3.2 Non-Functional Requirements

Non-functional requirements define performance criteria associated with usability, reliability, manufacturability, maintenance, and operational efficiency. In contrast with functional requirements, these specifications do not directly describe the extrusion process but establish quality conditions for system operation. Special attention was given to modularity, maintenance accessibility, and compatibility with widely locally available components to reduce manufacturing complexity and replacement costs. Additionally, mechanical safety and energy efficiency were considered essential to guarantee stable operation in a laboratory environment. The identified non-functional requirements are summarized in Table 2.

TABLE 2
Non-Functional Requirements of the Mechatronic Extrusion System.

ID	Engineering Performance Criteria	Metric / Validation Standard
RNF1	Usability & Maintenance	Accessible feeding hopper for rapid cleaning and maintenance
RNF2	Component Standardization	Use of commercially available 3D printer components
RNF3	Mechanical Safety	Structural integrity verified through FEA simulations
RNF4	Energy Efficiency	Efficient DC power infrastructure to reduce thermal losses

2.3.3 Constraints

The design process was bounded by practical constraints related to material behavior, local manufacturing limitations, available budget, and laboratory infrastructure. These restrictions established the operational limits which the final system must respect. Since PLA and PETG have different thermal behaviors and material properties, the extrusion process required independent material handling to prevent contamination and inconsistent melting characteristics. Similarly, moisture absorption characteristics demanded the implementation of a pre-drying stage before extrusion. Economic considerations also influenced several design decisions, particularly in the selection of commercially available components and the progressive prototyping strategy adopted. Additionally, the complete system was constrained to operate safely using standard 110V/60Hz laboratory electrical infrastructure while maintaining a compact desktop-scale footprint. Table 3 summarizes the principal constraints considered during the design process.

TABLE 3
Design and Operational Constraints.

ID	Constraint Category	Operational Limitation
C1	Material Separation Constraint	PLA and PETG flakes cannot be processed simultaneously
C2	Material Preparation Constraint	Plastic flakes must be dried before extrusion
C3	Economic Constraint	Manufacturing and electronics must remain within budget limits
C4	Physical & Electrical Constraint	Safe operation on 110V / 60Hz laboratory infrastructure

The systematic definition of requirements and constraints established the engineering base necessary for the conceptual and specific design phases described in the following sec-

tions.

2.4 Conceptual Design

After the system requirements and operational constraints were established, the conceptual design phase focused on translating the identified needs into feasible physical solutions. At this stage, the objective was not to define dimensions, materials, or specific components, but rather to identify the most suitable physical configuration capable of transporting, melting, and extruding material under controlled conditions. The conceptual development process emphasized the functional decomposition of the extrusion system into independent subsystems as the material feeding, thermal transformation, motion generation, filament shaping, and post-extrusion handling. Different architectural alternatives were evaluated according to their manufacturing feasibility, operational reliability, and spatial efficiency.

2.4.1 Functional Decomposition

The extrusion process was conceptually divided into four main stages: material feeding, transport and plastic melting, filament shaping, and material respooling. This process separation allowed the identification of the fundamental engineering functions required for continuous filament production. The first stage involved the intake of shredded PLA or PETG flakes into the extrusion channel through a feeding mechanism capable of ensuring continuous material delivery. Since irregular plastic flakes tend to exhibit poor flow and inconsistent packing density, the transport mechanism required a geometry capable of compressing and conveying material at the same time toward the heating region. The second stage focused on the thermomechanical transformation of the plastic. As the material advances through the barrel, the incoming particles are subjected to increasing pressure and temperature, this allows the transition from a solid granular state into a homogeneous viscous melt. The third stage consisted of shaping the molten polymer into a continuous strand through an outlet geometry. Since the final state required compatibility with FDM printers, the extrusion system needed to maintain dimensional stability around a nominal diameter of 1.75 mm. Finally, a post-processing stage was incorporated to regulate filament tension and facilitate controlled collection onto a spool. Based on these functional requirements, several architectural alternatives were evaluated before selecting the final machine configuration.

2.4.2 Alternative Analysis

Two architectural configurations were developed for the extrusion system. The first alternative consisted of a horizontal layout, in which material transport and extrusion occurred

parallel to the work surface. This arrangement is commonly adopted in commercial filament extruders due to its integration of cooling systems and accessibility to the extrusion zone. The second alternative proposed a vertical architecture, where the extrusion channel was aligned with the gravitational direction. In this configuration, material feeding occurs from the upper section of the machine through a hopper, allowing gravity to assist the downward movement of plastic flakes toward the screw channel.

To compare both alternatives, a Pugh matrix was implemented using weighted engineering criteria associated with manufacturing feasibility, operational reliability, sealing capability, spatial footprint, and cooling transition behavior. Table 4 presents the comparative evaluation conducted during the conceptual design phase.

TABLE 4
Pugh Matrix for Conceptual Design Selection.

Engineering Criteria	Weight	Cand. A (Rating)	Cand. A (Score)	Cand. B (Rating)	Cand. B (Score)
Manufacturing Feasibility	5	1	5	5	25
Operational Reliability	5	2	10	5	25
System Sealing	5	1	5	5	25
Footprint	3	3	9	4	12
Cooling Transition	3	5	15	2	6
Total Weighted Score			44		93

Candidate B: vertical configuration, obtained the highest weighted score and was selected as the preferred conceptual solution. Although the horizontal arrangement offered advantages regarding filament cooling accessibility, it presented greater risks associated with inconsistent material feeding and particle accumulation due to the irregular geometry and low packing density of shredded plastic particles. In contrast, the vertical configuration utilized from gravity-assisted feeding, which improved material transport continuity and reduced the probability of clogging at the screw inlet. Additionally, the vertical architecture reduced the overall workspace use and facilitated the mechanical isolation of thermal and electronic subsystems by distributing them along different sections of the machine. For these reasons, the vertical configuration was selected as the principal architecture for the specific design stage.

2.4.3 System Architecture

After selecting the system architecture, the mechatronic architecture of the system was defined by organizing the machine into integrated mechanical, thermal, electronic, and control subsystems. From a material and energy perspective, the system flow begins with the feeding hopper, where shredded plastic flakes are introduced into the barrel inlet. A rotating screw mechanism transports and compresses the material while the aluminum blocks mounted along the extrusion barrel heat it to its melting temperature. Once the polymer reaches a molten state, the material is forced through a nozzle to form a continuous filament. To maintain dimensional consistency after extrusion, a pulling mechanism positioned at the lower section regulates the linear extraction speed of the filament, while a spooler subsystem collects the final result. Since dimensional variation is strongly dependent on stretching conditions, both systems were designed to operate in coordination.

The electronic and control architecture was organized around an ESP32 microcontroller responsible for thermal regulation, motor coordination, and sensor data acquisition. Independent PID control loops were implemented to regulate each heating zone through temperature feedback provided by NTC thermistors. At the same time, an auxiliary Arduino Nano managed the human-machine interface (HMI), including the LCD display and rotary encoder, while maintaining serial communication with the ESP32 through a UART interface. The overall architecture also considered physical subsystem separation to improve thermal management and reduce electrical interference. High-current components, such as heater cartridges and motor drivers, were isolated from low-voltage sensing and control electronics to improve signal integrity and operational reliability.

2.5 Specific Mechatronic Design

Following the selection of the conceptual architecture, the specific mechatronic design phase focused on transforming the previously defined requirements into physical dimensions, subsystem specifications, control strategies, and integration criteria.

This stage considered the mechanical extrusion mechanism, the thermal system, the electronic control architecture, the human-machine interface, and the electrical power distribution required for the complete implementation of the prototype. The design process was developed to integrate mechanical transport, thermal energy transfer, motor actuation, embedded control, and operator interaction into a single coordinated system.

Analytical calculations were used to estimate screw geometry, theoretical extrusion ca-

capacity, filament pulling speed, torque requirements, and power consumption. Additionally, simulation tools were considered to support the structural and thermal verification of critical components before fabrication and assembly.

2.5.1 Mechanical Subsystem Design

The mechanical subsystem was designed to transport, compress, melt, and extrude shredded material through a single-screw extrusion mechanism. Since the system objective is to process irregular PLA and PETG flakes, the screw geometry, barrel dimensions, torque capacity, and pulling velocity were defined as critical design variables.

2.5.1.1 Barrel and Screw Geometry. The extrusion barrel was designed using AISI 304 stainless steel due to its corrosion resistance, mechanical durability, and thermal stability under the operating temperature range required for PLA and PETG processing. The barrel inner diameter was defined as 18.22 mm, providing a compact extrusion channel while maintaining sufficient mechanical clearance for the rotating screw inside of it. The extrusion screw was designed using SAE 1045 steel due to its machinability and resistance to torsional loads. The screw outer diameter was defined as 18.00 mm, with a total functional length of 250 mm. A screw pitch of 18.00 mm was selected to simplify manufacturing while maintaining an adequate material transport capacity. The diametral clearance between the barrel and screw was calculated according to Equation 2.1.

$$C_d = D_b - D_s \quad (2.1)$$

$$C_d = 18.22 - 18.00 = 0.22\text{mm} \quad (2.2)$$

where C_d is the diametral clearance, D_b is the barrel inner diameter, and D_s is the screw outer diameter. Therefore, the corresponding radial clearance was estimated as:

$$C_r = \frac{C_d}{2} \quad (2.3)$$

$$C_r = \frac{0.22}{2} = 0.11\text{mm} \quad (2.4)$$

This clearance was selected to reduce excessive polymer backflow while avoiding mechanical interference between the rotating screw and the internal surface of the barrel. Since

the extrusion process requires progressive material densification, a compression ratio of 3:1 was established. This ratio was obtained by reducing the screw channel depth from the feed section to the metering section. The screw feed channel depth was calculated as:

$$H_f = \frac{D_s - D_{core,f}}{2} \quad (2.5)$$

$$H_f = \frac{18.00 - 10.00}{2} = 4.00\text{mm} \quad (2.6)$$

The metering or transitional channel depth was calculated as:

$$H_m = \frac{D_s - D_{core,m}}{2} \quad (2.7)$$

$$H_m = \frac{18.00 - 15.34}{2} = 1.33\text{mm} \quad (2.8)$$

The resulting compression ratio was determined according to Equation 2.9.

$$CR = \frac{H_f}{H_m} \quad (2.9)$$

$$CR = \frac{4.00}{1.33} \approx 3.0 \quad (2.10)$$

The selected compression ratio objective is to improve material compaction, reduce internal voids, and promote a more homogeneous transition from solid flakes to molten polymer before the material reaches the nozzle.

2.5.1.2 Volumetric Flow Rate Estimation. The theoretical extrusion capacity of the system was estimated by calculating the drag flow produced by the screw inside the metering channel. This calculation was used as a preliminary sizing parameter for the pulling mechanism and does not represent the final experimental extrusion rate, since real extrusion performance is affected by melt viscosity, die pressure, leakage flow, incomplete melting, particle geometry, and friction with the barrel. The surface velocity component contributing to material transport was estimated as:

$$V_s = \pi D_s N \cos(\phi) \quad (2.11)$$

where D_s is the screw diameter, N is the screw rotational speed, and ϕ is the screw helix angle. For a nominal speed of 20 RPM:

$$N = \frac{20}{60} = 0.333\text{rev/s} \quad (2.12)$$

Considering a helix correction factor of $\cos(\phi) \approx 0.953$, the surface velocity was estimated as:

$$V_s = \pi(18.00)(0.333)(0.953) \quad (2.13)$$

$$V_s \approx 17.96\text{mm/s} \quad (2.14)$$

Due to the reduced open channel area generated by the screw flight and the compact geometry of the prototype, a conservative effective channel width of $W_{eff} = 15.65$ mm was considered for the theoretical drag flow estimation. The volumetric drag flow was calculated according to Equation 2.15.

$$Q_d = 0.5 \cdot W_{eff} \cdot H_m \cdot V_s \quad (2.15)$$

$$Q_d = 0.5(15.65)(1.33)(17.96) \quad (2.16)$$

$$Q_d \approx 187\text{mm}^3/\text{s} \quad (2.17)$$

Converting this value to minutes:

$$Q_d \approx 187 \times 60 \quad (2.18)$$

$$Q_d \approx 11220\text{mm}^3/\text{min} \quad (2.19)$$

The corresponding hourly volumetric production rate was estimated as:

$$V_h = \frac{Q_d \times 60}{1000} \quad (2.20)$$

$$V_h = \frac{11220 \times 60}{1000} \quad (2.21)$$

$$V_h \approx 673.2 \text{ cm}^3/\text{h} \quad (2.22)$$

Using the approximate densities of PLA and PETG, the theoretical mass flow rate was estimated according to Equation 2.23.

$$\dot{m} = V_h \cdot \rho \quad (2.23)$$

for PLA, considering $\rho_{PLA} = 1.24 \text{ g/cm}^3$:

$$\dot{m}_{PLA} = 673.2 \times 1.24 \quad (2.24)$$

$$\dot{m}_{PLA} \approx 834.8 \text{ g/h} \quad (2.25)$$

for PETG, considering $\rho_{PETG} = 1.27 \text{ g/cm}^3$:

$$\dot{m}_{PETG} = 673.2 \times 1.27 \quad (2.26)$$

$$\dot{m}_{PETG} \approx 854.9 \text{ g/h} \quad (2.27)$$

These values represent an ideal theoretical production capacity under simplified drag-flow conditions. Therefore, they were used only as reference values for preliminary subsystem sizing and not as final experimental production results.

2.5.1.3 Linear Filament Velocity. To define the baseline operating condition of the pulling subsystem, the required linear velocity was estimated from the continuity relationship between volumetric flow rate and filament cross-sectional area. The target filament diameter was defined as 1.75 mm to ensure compatibility with conventional FDM 3D printers. The cross-sectional area of the filament was calculated as:

$$A_f = \frac{\pi d_f^2}{4} \quad (2.28)$$

$$A_f = \frac{\pi(1.75)^2}{4} \quad (2.29)$$

$$A_f \approx 2.41\text{mm}^2 \quad (2.30)$$

The theoretical pulling velocity was then calculated as:

$$V_l = \frac{Q_d}{A_f} \quad (2.31)$$

$$V_l = \frac{11220}{2.41} \quad (2.32)$$

$$V_l \approx 4656\text{mm/min} \quad (2.33)$$

$$V_l \approx 4.66\text{m/min} \quad (2.34)$$

This value was used as a reference for the pulling subsystem. In physical operation, the pulling speed must be adjusted according to the actual extrusion flow, cooling behavior, and measured filament diameter.

2.5.1.4 Torque Estimation and Powertrain Selection. To ensure the correct working of the system, the extrusion screw requires optimal torque to overcome the resistance generated by material compaction, polymer viscosity, internal friction, and die pressure. Since polymer extrusion involves variable loads, especially during startup and feeding of irregular flakes, the powertrain was sized with an additional safety factor. The shear rate inside the metering section was estimated according to Equation 2.35.

$$\dot{\gamma} = \frac{\pi D_s N}{H_m} \quad (2.35)$$

Substituting the operating parameters:

$$\dot{\gamma} = \frac{\pi(18.00)(0.333)}{1.33} \quad (2.36)$$

$$\dot{\gamma} \approx 14.17\text{s}^{-1} \quad (2.37)$$

Considering an estimated viscosity of PETG melt at elevated temperature of $\eta \approx 2700$ Pa·s, the shear stress was estimated as:

$$\tau = \eta \cdot \dot{\gamma} \quad (2.38)$$

$$\tau = 2700(14.17) \quad (2.39)$$

$$\tau \approx 38259\text{Pa} \quad (2.40)$$

Based on the estimated viscous resistance in the transition section, the theoretical viscous torque requirement was estimated as:

$$T_v \approx 1.62\text{Nm} \quad (2.41)$$

To address fluctuations associated with solid friction, compacted plastic flakes, startup resistance, die pressure losses, and manufacturing tolerances, an engineering safety factor of four was applied:

$$T_{op} = T_v \cdot FS \quad (2.42)$$

$$T_{op} = 1.62 \times 4 \quad (2.43)$$

$$T_{op} = 6.48\text{Nm} \quad (2.44)$$

Based on this requirement, a NEMA 23 stepper motor with a 15.3:1 reduction gearbox was selected. This powertrain component is capable of providing approximately 15.5 Nm of output torque. The mechanical safety factor was estimated as:

$$FS_m = \frac{T_{available}}{T_{required}} \quad (2.45)$$

$$FS_m = \frac{15.5}{6.48} \quad (2.46)$$

$$FS_m \approx 2.39 \quad (2.47)$$

Therefore, the selected powertrain provides sufficient theoretical torque capacity for the extrusion mechanism while maintaining a safety margin against load variations during operation.

2.5.2 Structural Design and Simulation Setup

The motor support structure was designed to maintain alignment between the stepper motor, the extrusion screw and the extrusion barrel while supporting the load generated by the motor assembly. Since shaft misalignment can increase friction, and reduce the efficiency of torque transmission, the rigidity of the support plate was considered an important design criterion to take into account. A finite element analysis was formulated using Autodesk Inventor 2025 to evaluate the mechanical behavior of the motor support plate under static loading conditions. The support plate was modeled as an aluminum structural component attached to the machine frame through bolted regions. The gravitational load of the NEMA 23 motor and gearbox assembly was represented as a concentrated force of 29.43 N applied at the motor mounting interface. The boundary conditions were assigned by constraining the bolted regions connected to the aluminum extrusion frame. The simulation outputs considered for design verification were vertical displacement along the Y-axis and Von Mises equivalent stress. The displacement analysis was used to evaluate possible structural sagging, while the Von Mises criterion was selected to identify potential yielding regions in the metallic support plate.

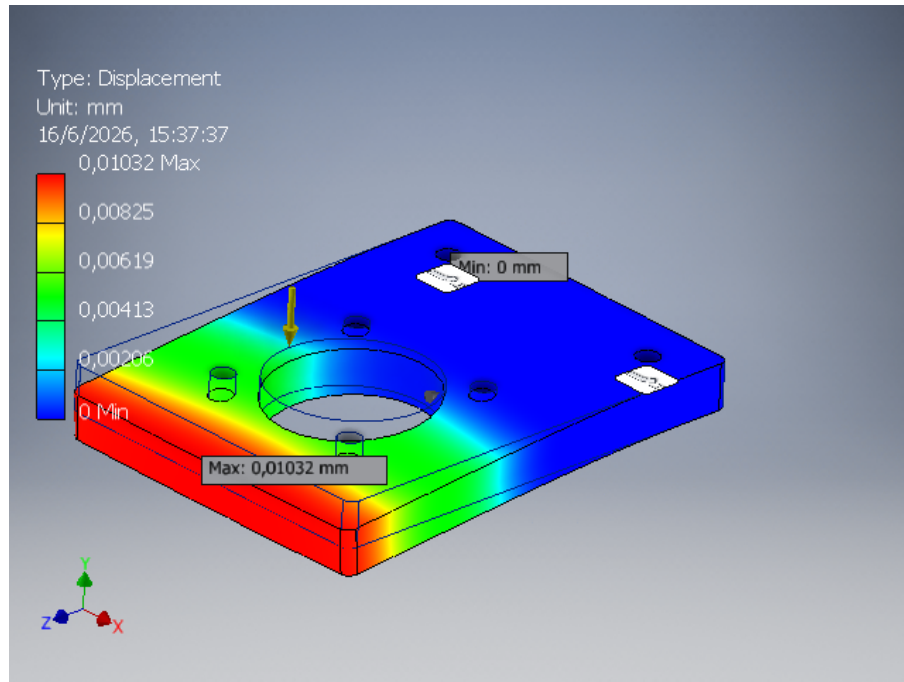


Fig. 2. Finite element analysis setup and displacement output of the motor support plate under a concentrated motor load of 29.43 N.

The displacement contour plot allows for a localized assessment of structural deflection under the powertrain's mass. The distribution indicates that while the greatest structural deflection occurs at the geometric center of the motor mounting interface due to the overhanging configuration, the maximum magnitude remains safely within acceptable operational margins to prevent shaft deflection. This confirms that the thickness and geometry of the plate provide adequate bending stiffness to prevent angular misalignment between the gearbox output shaft and the extrusion screw during operation.

To complement the stiffness evaluation, it is necessary to analyze the internal stress distribution to guarantee that no region exceeds the yield strength of the selected material. Figure 3 shows the corresponding Von Mises stress distribution obtained from the finite element model.

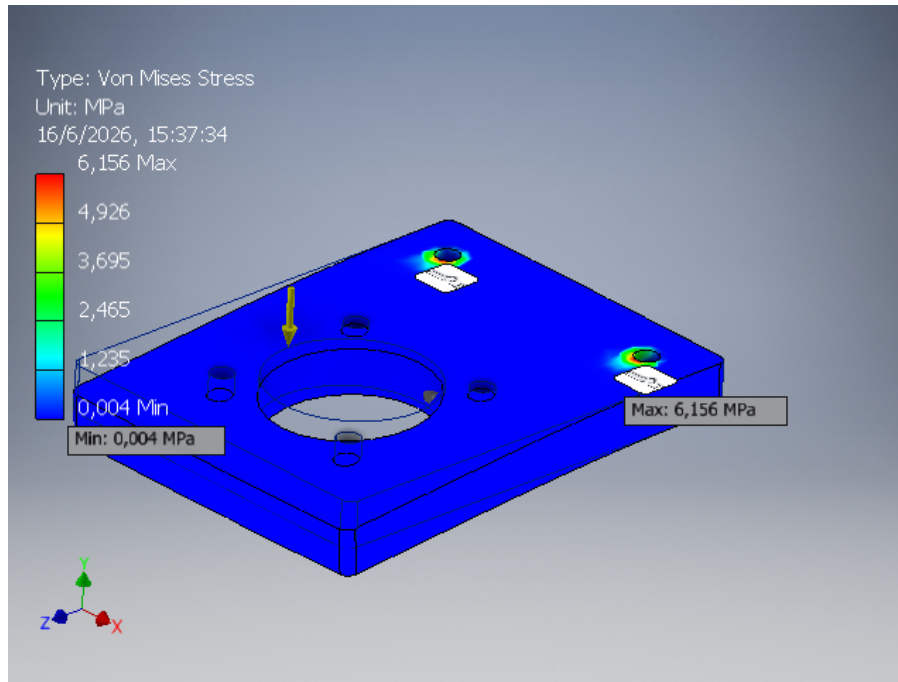


Fig. 3. Von Mises stress output considered for structural verification of the motor support plate.

The structural simulation was used as a design verification tool to identify whether the support plate geometry could maintain motor alignment under the expected static load condition before final assembly.

2.5.3 Thermal Subsystem Design and Simulation Setup

The thermal subsystem was designed to provide controlled heat transfer to the extrusion barrel during polymer plastification. Since PLA and PETG require different processing temperatures, the heating system was divided into three independently controlled thermal zones distributed along the barrel. The thermal part of the barrel is placed on its end dividing it in three equal parts: Zone 1 is described as the nozzle part of the extruder, Zone 3 is the middle of the barrel and Zone 2 is placed in the middle of Zones 1 and 3.

Each thermal zone consisted of an aluminum 7075 heater block coupled to a 24 V and 50 W heater (a cartridge type) and a 100k NTC thermistor for temperature feedback. Aluminum 7075 was selected for the heating blocks due to its thermal conductivity, which facilitates heat transfer from the cartridge heater to the stainless-steel barrel. The barrel is fabricated from AISI 304 stainless steel due to its corrosion resistance, mechanical strength, and thermal stability. For PLA processing, the nominal temperature profile was defined as 190°C, 200°C, and 210°C for Zones 1, 2, and 3, respectively. For PETG processing, higher setpoints can be configured according to material requirements.

A steady-state thermal simulation was defined in SolidWorks 2024 to evaluate the heat propagation behavior of the proposed heating configuration before physical testing. The simulated assembly included the three aluminum heating blocks, the stainless steel barrel, and the heat input generated by the cartridge heaters. The objective of the simulation was to verify the spatial distribution of heat along the barrel and to identify possible temperature discontinuities between heating zones**, as presented in the thermal distribution of Figure 4**.

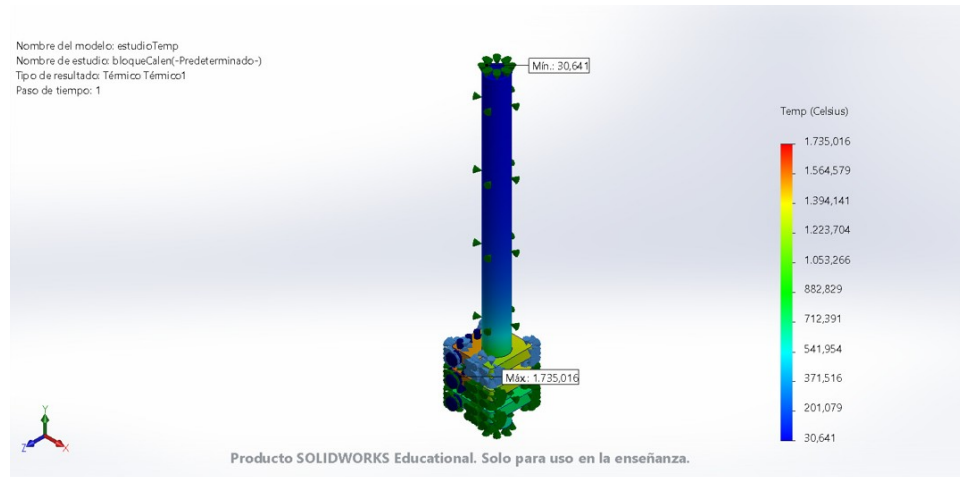


Fig. 4. Steady-state thermal simulation setup of the extrusion barrel and three-zone heating block assembly in SolidWorks 2024.

The thermal simulation was used as a preliminary design verification tool to support heater placement, thermal zone distribution, and material selection before prototype assembly.

2.5.4 Electronics and Control Architecture

The electronics and control architecture was developed to coordinate thermal regulation, motor control, sensor acquisition, user interaction, and communication between subsystems. A distributed control strategy was adopted in order to separate real-time process control from the human-machine interface.

The ESP32 microcontroller was chosen as the main controller of the extrusion system. It was responsible for temperature control, heater activation, stepper motor coordination (extruder, puller and spooler motors), sensor acquisition, and communication with the HMI module. It was selected because of its processing capability, PWM generation, and compatibility with embedded control tasks between its two cores (one for motor activation and coordination and other for the rest of the tasks).

An Arduino Nano was incorporated as an auxiliary microcontroller dedicated to the human-machine interface. This microcontroller was in charge of the LCD display, rotary en-

coder, RUN/STOP button, and buzzer. Separating the HMI from the main control unit reduced the computational load on the ESP32 and simplified the firmware structure during debugging and testing as electronic noise was present in sensor signals. Communication between the ESP32 and Arduino Nano was implemented through a UART serial interface operating at 9600 baud during the initial testing stage. Since the ESP32 operates at 3.3 V logic and the Arduino Nano operates at 5 V logic, a bidirectional logic level converter was used to ensure voltage compatibility between both microcontrollers.

2.5.4.1 Thermal Control Strategy. Temperature regulation was implemented through three independent PID control loops, one for each heating zone. Each loop used an NTC thermistor as the feedback sensor and controlled the activation of a 24 V cartridge heater through a power switching stage. The PID controller calculates the control output according to the temperature error between the measured value and the desired setpoint. The general form of the PID control law is shown in Equation 2.48.

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (2.48)$$

where $u(t)$ is the controller output, $e(t)$ is the temperature error, K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain.

The proportional component improves the response speed of the system, the integral component reduces steady-state error, and the derivative component contributes to reducing overshoot and oscillatory behavior. The three independent control loops allow each heating zone to maintain the target temperatures, improving thermal regulation along the extrusion barrel.

2.5.4.2 Motor Control Strategy. The mechanical movement of the extrusion screw, pulling mechanism, and spooler was generated using stepper motors driven by external drivers. The extruder screw was coupled to the NEMA 23 motor driven by a DM542 driver, while the pulling and spooler subsystems were actuated by NEMA 17 motors controlled through TB6600 drivers. The ESP32 generated the STEP and DIR signals required by the motor drivers. This architecture allowed independent control of each motor while maintaining synchronization between extrusion, pulling, and respooling. The extruder motor was configured to operate at a nominal output speed of 20 RPM initially, then adjusted in testing, while the pulling motor speed was defined according to the theoretical filament velocity and adjusted during testing. The pulling

subsystem was designed to regulate filament extraction after the nozzle. Since filament diameter depends on the relationship between extrusion flow, temperature and pulling speed.

2.5.4.3 Sensor Integration. The system incorporated temperature sensors, user input devices, and a Hall-effect sensing mechanism to measure filament diameter. The three NTC 100K thermistors provided feedback for the thermal control loops, while the KY-040 rotary encoder and RUN/STOP button allowed local user interaction through the HMI.

To monitor filament diameter, an analog Hall-effect sensor UGN3503 was integrated with a mechanical lever mechanism. The sensing system consists of a pivoted lever that remains in contact with the filament surface that goes through 2 ball bearings to allow its slide. Variations in filament diameter produce small linear displacements of the lever, which are mechanically amplified and translated into changes in the distance between a permanent neodymium magnet and the UGN3503 sensor. Since the UGN3503 generates an analog voltage proportional to the magnetic field intensity, changes in the magnet-to-sensor distance produce measurable voltage variations. These voltage changes are acquired by the ESP32 analog-to-digital converter and correlated with the corresponding filament diameter through a calibration procedure that consist to take values of three different diameters as: nothing between the bearings, a 1.75 mm commercial filament, and a 2.5 mm diameter tool.

The lever-based measurement approach was selected because it allows non-destructive monitoring of filament dimensions while maintaining a simple and low-cost implementation. Unlike digital Hall sensors that only provide switching information, the analog output of the UGN3503 allows continuous measurement of displacement and therefore continuous estimation of filament diameter. The sensing principal mechanism is illustrated in Figure 5, where the filament displacement causes the lever to rotate, modifying the relative position between the magnet and the Hall-effect sensor.



Fig. 5. Lever-based filament diameter measurement system.

After the mentioned calibration, the measured voltage can be converted into filament diameter values and displayed through the HMI. This modular sensing architecture allows dimensional monitoring and control to be incorporated without requiring significant modifications to the thermal, mechanical, or control subsystems.

2.5.5 Human–Machine Interface Design

The human-machine interface was implemented as the operator interaction layer of the extrusion system. Its purpose is to allow to select the material, supervise the temperatures, pulling control, and process monitoring through a compact embedded interface based on a 20×4 LCD display and a rotary encoder. The ESP32-Nano distributed architecture improved modularity and allowed the interface to operate independently from the thermal and motor control routines.

2.5.5.1 HMI Architecture. The HMI hardware consisted of a 20×4 I²C LCD display, a KY-040 rotary encoder with integrated push button, a dedicated push button, and a buzzer. The LCD provided visual feedback of process variables and system states, while the encoder allowed menu navigation and confirmation. The push button provided direct control of the pulling subsystem, and the buzzer generated audible feedback while the user interacted with the interface and system notifications. The Arduino Nano communicated with the ESP32 through UART serial communication. The bidirectional logic level converter allowed safe communication between the 5 V logic level of the Arduino Nano and the 3.3 V logic level of the ESP32. This

complete hardware description is detailed in the block diagram of Figure 6.

Human–Machine Interface (HMI) Architecture

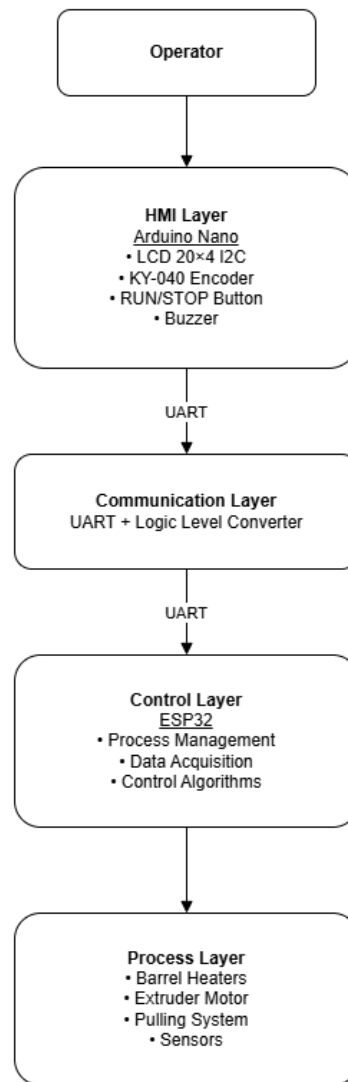


Fig. 6. Block architecture of the implemented human–machine interface and its communication with the extrusion control system.

This architecture allows the operator to interact with the extrusion system without directly interfering with the thermal and motor control routines executed by the ESP32.

2.5.5.2 HMI Menu Structure. The HMI menu structure was designed to organize the main operating functions of the filament extrusion system in a simple navigation scheme suitable for a 20×4 LCD display. The interface was structured around a main menu that provides access to material selection, preheating supervision, pulling control, and process monitoring. The main menu acts as the central navigation point of the interface. From this screen, the operator can move between the available options by rotating the KY-040 encoder. Pressing the en-

coder confirms the selected option and transfers the interface to the corresponding operational screen. The HMI menu structure was designed to organize the main operating functions of the filament extrusion system in a simple navigation scheme suitable for a 20×4 LCD display. The interface was structured around a main menu that provides access to material selection, preheating supervision, pulling control, and process monitoring. The main menu acts as the central navigation point of the interface. From this screen, the operator can move between the available options by rotating the KY-040 encoder. Pressing the encoder confirms the selected option and transfers the interface to the corresponding operational screen. The implemented menu options were *Material*, *Preheat*, *Pulling*, and *Info*, as illustrated in Figure 7.

The material selection screen allows the operator to choose between predefined polymer profiles. The preheating screen displays the measured and target temperatures of the three heating zones. The pulling screen displays the operating state of the pulling subsystem. Finally, the information screen provides a compact monitoring view of the main process variables.

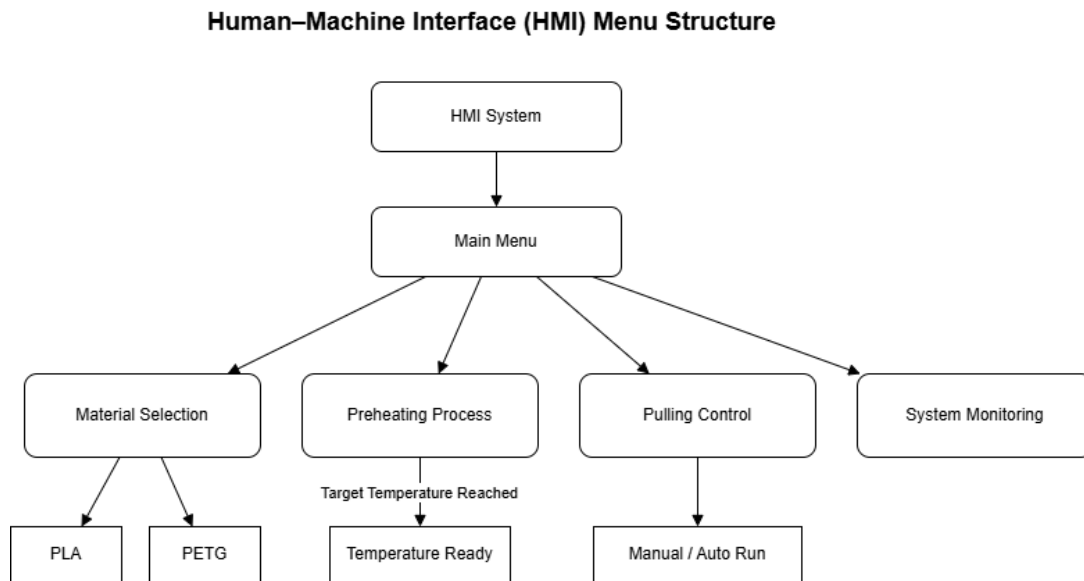


Fig. 7. Menu structure implemented in the human–machine interface of the filament extrusion system.

The implemented structure provides a compact navigation scheme that allows the operator to access the principal operating functions without requiring complex input devices.

2.5.5.3 HMI Navigation Logic. The navigation logic of the HMI was implemented using a finite-state structure in which each interface screen corresponds to a defined software state. This approach was selected to ensure predictable transitions between screens and to simplify the embedded implementation of the user interface. The main states implemented in the

firmware were system initialization, main menu, material selection, preheating, temperature ready, pulling control, and system monitoring.

During startup, the interface enters the initialization state, where a boot message is displayed and the buzzer provides an acoustic indication. After the initialization delay, the HMI automatically transitions to the main menu. In the main menu state, encoder rotation modifies the selected option cyclically. Pressing the encoder transfers the interface to the selected function, which can correspond to material selection, preheating, pulling control, or system monitoring.

In the material selection state, encoder rotation switches between the available material profiles. Pressing the encoder confirms the selected profile, loads the corresponding temperature setpoints, and returns the system to the main menu.

In the preheating state, the interface continuously updates the measured and target temperatures of the three heating zones. When the measured temperatures reach their respective setpoints, the system changes to the temperature ready state and generates an acoustic notification through the buzzer. Pressing the encoder from this state returns the interface to the main menu.

The pulling control state allows the operator to supervise the pulling subsystem. The RUN/STOP push button operates independently from the encoder navigation and toggles the pulling state between stopped and running conditions. When the interface is displaying the pulling control screen, the LCD is updated immediately to reflect the new operating condition.

An automatic timeout mechanism was implemented to improve process supervision. If no user interaction is detected for 10 seconds, the interface automatically redirects the operator to the system monitoring screen. This behavior ensures that the main process variables remain visible during idle periods. The complete state transition logic of the interface is detailed in Figure 8.

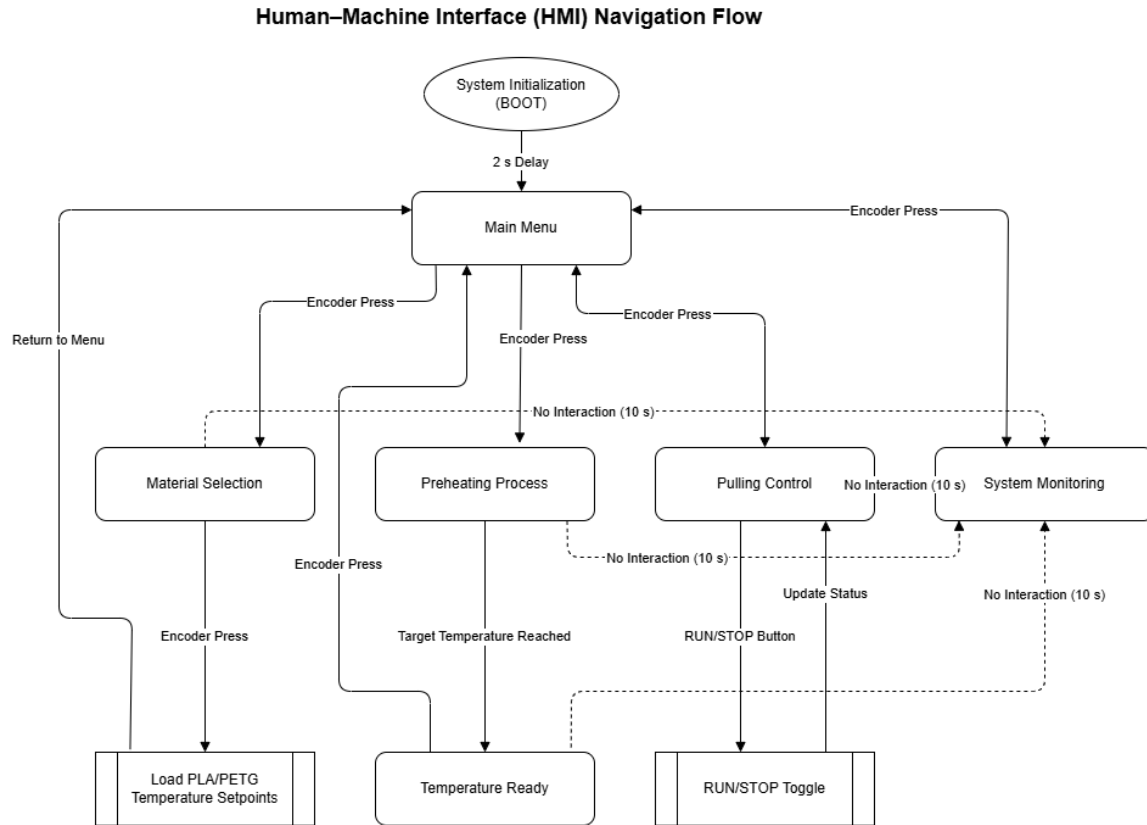


Fig. 8. Navigation flow implemented in the HMI firmware of the filament extrusion system.

The implemented navigation logic provides a simple and robust interaction model based on a limited number of physical inputs. This design reduces hardware complexity while maintaining access to the main configuration, control, and monitoring functions required during operation.

2.5.6 Power Architecture

The electrical power architecture was designed to satisfy the energy consumption of the extrusion process while maintaining operational safety, electrical stability, and signal integrity. The system included high-current components, such as heater cartridges and stepper motor drivers, as well as low-power control components, such as the ESP32, Arduino Nano, LCD display, encoder, buzzer, sensors, and logic level converter. To reduce electrical noise and improve system reliability, the power architecture was divided into a high-power stage and an auxiliary control stage. Table 5 presents the estimated current and power consumption of the main electrical components.

TABLE 5
Electrical Current and Power Consumption Breakdown for Power Supply Sizing.

Component	Qty.	Voltage (V)	Current (A)	Power (W)
NEMA 23 Extruder Motor with Gearbox	1	24	2.84	68.16
NEMA 17 Puller Motor	1	24	1.50	36.00
NEMA 17 Spooler Motor	1	24	1.50	36.00
Heater Cartridges	3	24	6.25	150.00
DM542 Driver	1	24	0.15	3.60
TB6600 Drivers	2	24	0.20	4.80
Cooling Fans	3	12	0.50	6.00
ESP32	1	5	0.24	1.20
Arduino Nano	1	5	0.05	0.25
Logic Level Converter	1	5	0.01	0.05
KY-040 Encoder	1	5	0.005	0.03
LCD 20x4 I2C	1	5	0.08	0.40
Buzzer	1	5	0.03	0.15
UGN3503 Hall Sensor	1	5	0.01	0.05
Total Estimated Power		24	12.77	306.69

The required power capacity was estimated by applying a 25% engineering margin to the theoretical total power demand:

$$P_{required} = P_{total} \times 1.25 \quad (2.49)$$

$$P_{required} = 306.69 \times 1.25 \quad (2.50)$$

$$P_{required} = 383.36W \quad (2.51)$$

Although the application of the 25% margin suggests a higher rated supply, the implemented prototype used a distributed power architecture due to budget limitations and component availability. A 24 V, 15 A switched-mode power supply was selected for the high-power stage, providing up to 360 W for the heater cartridges and stepper motor drivers. The estimated 24 V load was approximately 298.56 W under theoretical simultaneous operation, remaining below the rated capacity of the selected source.

An auxiliary isolated 12 V, 5 A power supply was incorporated for the control and instrumentation stage. This supply provided power to the 5 V electronic components, including the ESP32, Arduino Nano, LCD display, encoder, buzzer, logic level converter, and Hall sensor through voltage regulation in its own potentiometer.

The separation between the high-power stage and the control stage was implemented to reduce electromagnetic interference and voltage variations. Heater switching and stepper motor operation can generate electrical noise capable of affecting sensor readings and serial communication. That's why, isolating the control electronics from the electromechanical loads improved measurement stability, signal integrity, and operational reliability. For future versions of the system, a 24 V, 20 A power supply is recommended if the 25% safety margin is applied strictly to the high-power stage.

2.5.7 Manufacturing and Assembly Considerations

The physical implementation of the extrusion system required the integration of machined, structural, thermal, and electronic components. The screw and barrel assembly represented the most critical mechanical interface because proper alignment is necessary to reduce friction, avoid mechanical interference, and maintain stable torque transmission.

The barrel was mechanically integrated with the heater blocks to improve heat transfer along the extrusion region. The heating blocks were positioned along the barrel to create three thermal zones corresponding to the feed, compression, and metering regions of the screw. The nozzle was installed at the outlet of the barrel to define the final filament shape.

Mechanical fixation of the barrel was considered essential to prevent unwanted rotation during screw operation. Since the screw transmits torque to the material and generates reaction forces inside the barrel, the barrel must be constrained by an anti-rotation mechanism or rigid support. Without this constraint, the barrel may rotate together with the screw, reducing relative motion between the screw and the material and preventing effective extrusion, or also the tangling of cables.

The electronics were physically separated from the heated section of the machine to reduce thermal exposure and improve maintenance accessibility. High-current wiring associated with heaters and stepper drivers was routed separately from low-voltage signal wiring used by sensors, communication lines, and the HMI. These assembly considerations were used to improve the reliability, maintainability, and safety of the prototype during testing.

2.5.8 Risk Assessment and Mitigation Strategies

Table 6 summarizes the principal engineering risks identified during the specific design phase of the mechatronic extrusion system, along with the corresponding mitigation strategies defined to reduce their probability of occurrence or potential impact on prototype performance.

TABLE 6
Identified Engineering Risks and Mitigation Strategies.

Risk	Mitigation Strategy
Barrel co-rotation caused by adhesion between softened polymer and internal barrel wall, preventing relative screw motion and stable extrusion.	Install a mechanical anti-rotation constraint on the barrel support structure to prevent barrel displacement during screw operation.
Insufficient torque generation during startup or high-viscosity material processing, causing screw stall or incomplete material transport.	Size the powertrain with a mechanical safety factor greater than 2 and implement a soft-start ramp in the motor driver firmware to reduce abrupt current peaks at startup.
Thermal overshoot and extended settling time in the inlet heating zone (Zone 3), causing localized overheating of the polymer during the initial transient.	Apply conservative PID tuning with emphasis on overshoot reduction and incorporate thermal insulation around the barrel to improve temperature uniformity between heating zones.

TABLE 6
Identified Engineering Risks and Mitigation Strategies.

Risk	Mitigation Strategy
Excessive filament stretching due to mismatch between material flow rate at the nozzle and pulling subsystem speed, resulting in reduced filament diameter.	Adjust pulling speed systematically relative to screw speed and implement a lever-based Hall-effect diameter sensing system to support future closed-loop pulling speed control.
Moisture absorption in PETG material prior to extrusion causing hydrolytic degradation, vapor bubble formation, and internal porosity in the extrudate.	Establish a mandatory pre-drying procedure for PETG material before each extrusion session to reduce residual humidity and prevent bubble-related defects.
Inadequate screw compression geometry producing insufficient pressure build-up at the nozzle, resulting in discontinuous flow or porous filament.	Define a 3:1 compression ratio with progressive channel depth reduction from the feed to the metering section, and evaluate alternative screw configurations if instabilities are observed.
Electrical noise generated by heater switching and stepper motor drivers interfering with low-voltage sensor signals and UART serial communication.	Physically separate high-current wiring from low-voltage signal lines and power the control electronics from an isolated auxiliary power supply.
Firmware instability in the HMI navigation state machine causing unintended screen transitions or encoder misdetection during extended operation.	Implement encoder debounce logic in firmware and validate all navigation state transitions prior to integrated extrusion testing.

TABLE 6
Identified Engineering Risks and Mitigation Strategies.

Risk	Mitigation Strategy
Logic level incompatibility between the ESP32 (3,3 V) and Arduino Nano (5 V) causing communication errors or component damage through the UART interface.	Incorporate a bidirectional logic level converter between both microcontrollers to ensure voltage-compatible serial communication.
Structural misalignment between the motor shaft and extrusion screw generating radial loads, increased friction, and reduced torque transmission efficiency.	Verify motor support plate rigidity through finite element analysis and constrain the motor mounting interface to maintain coaxial alignment during operation.

Chapter III

Results & Discussion

3.1 Obtained Results

3.1.1 Assembled Prototype

The integrated prototype of the filament extrusion and recycling system was assembled on a structural aluminum 20×20 mm V-profile frame. The final system was composed of three main physical subsystems: the extrusion tower with the drive motor and material feeding unit, the puller and spooler unit, and the electronic control and HMI enclosure. Figure 9 shows the complete assembled prototype, where the spatial arrangement of the three subsystems along the aluminum frame can be observed.

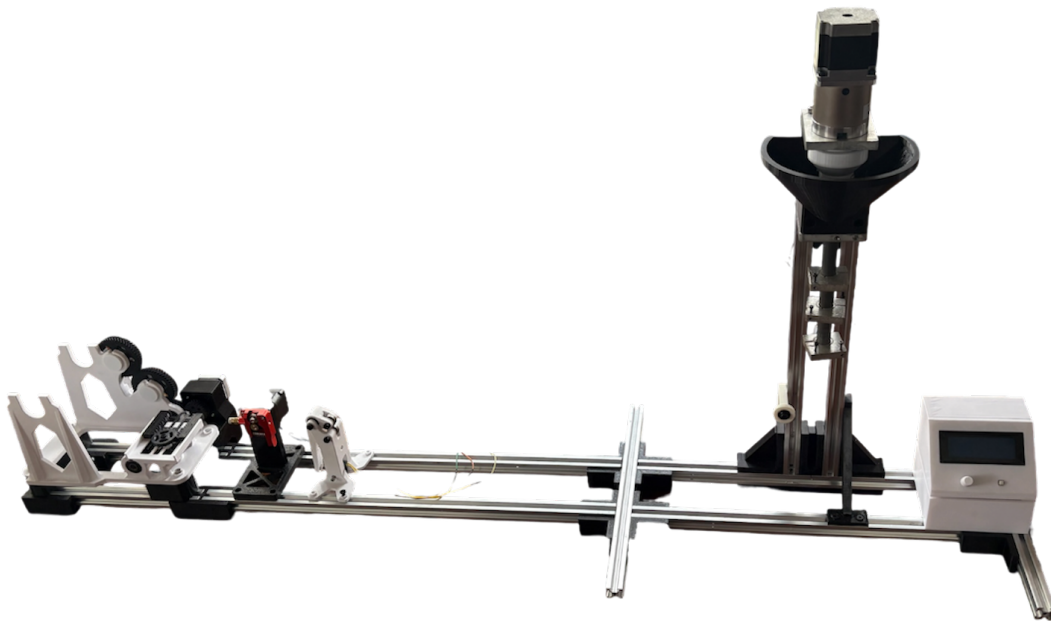


Fig. 9. Complete assembled prototype. From left to right: puller and spooler subsystem, extrusion tower with NEMA 23 motor and hopper, and HMI control enclosure.

The puller and spooler subsystem was positioned at the base of the frame to receive the extruded filament directly after it exits the nozzle and passes through the cooling zone. Figure 10 shows a detail of this subsystem, which consists of two independent NEMA 17 stepper motors: one driving the traction rollers responsible for filament pulling, and one driving the spool winding mechanism. The structural components of this subsystem, including the roller housings and motor mounts, were fabricated using FDM 3D printing, which allowed rapid iteration and low-cost manufacturing of custom geometry parts.

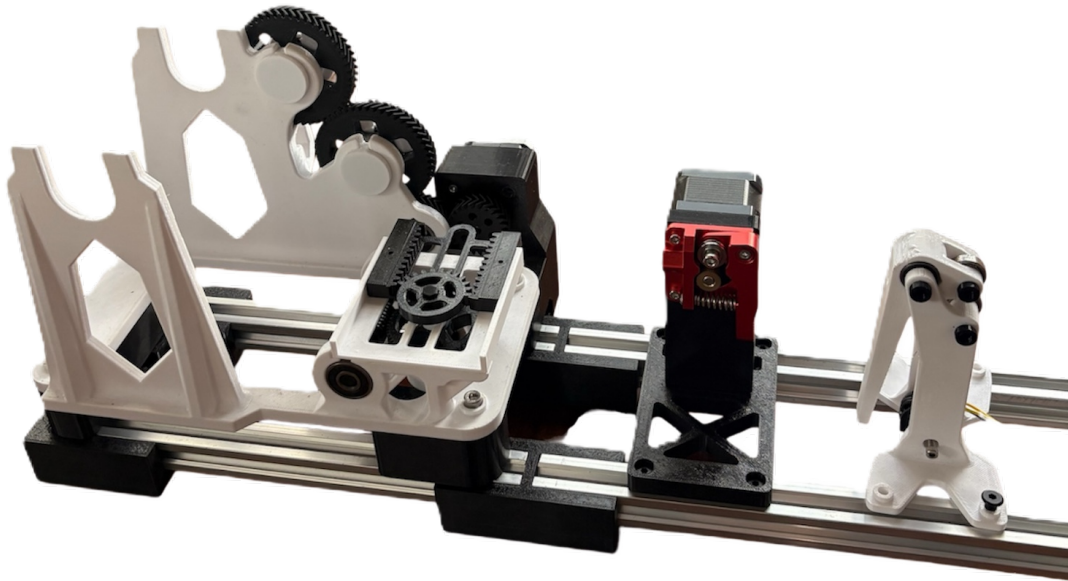


Fig. 10. Detail of the puller and spooler subsystem.

The extrusion tower and the HMI enclosure are shown in Figure 11. The tower integrates the NEMA 23 stepper motor with a 15:1 planetary gearbox at its upper section, connected directly to the extrusion screw through a rigid coupling. The material hopper is mounted at the barrel inlet to allow manual feeding of shredded thermoplastic flakes. The heated barrel and nozzle assembly are located in the lower section of the tower, where the three independently controlled heating zones are distributed. The HMI enclosure, mounted adjacent to the tower, houses the LCD 20×4 display and the KY-040 rotary encoder, providing the operator interface for process configuration and monitoring.



Fig. 11. Extrusion tower and HMI control enclosure.

The assembled prototype allowed the individual validation of the thermal, motor, communication, and HMI subsystems before conducting extrusion trials. This modular validation approach was useful to identify mechanical and control limitations without compromising the complete system during early testing.

3.1.2 Thermal Control Subsystem Results

The closed-loop PID thermal control subsystem was validated independently for each of the three heating zones. These tests were performed to evaluate the transient response, overshoot, settling time, and steady-state error of the thermal control loop. The PID response curves were previously presented as part of the control behavior characterization and are not repeated in this section.

It is important to note that the PID validation tests and the extrusion trials were conducted as independent experimental procedures. The PID tests were used to verify the capability of the control system to reach and maintain assigned thermal setpoints under controlled conditions. In contrast, the extrusion trials used a different temperature profile selected for PLA processing during material feeding and filament production. Therefore, the PID performance metrics reported in Table 7 validate the thermal control capability of the system, but they do not represent the exact temperature profile used during the final extrusion trials.

TABLE 7
Closed-Loop PID Thermal Validation Performance Metrics per Heating Zone.

Zone	SP (°C)	T_0 (°C)	t_c (s)	T_{pk} (°C)	OS (°C)	OS (%)	t_s (s)	SSE (°C)
Z1 – Nozzle	195	25	~800	201	+6	3.1	~900	≤ 1
Z2 – Center	185	25	~800	193	+8	4.3	~950	≤ 1
Z3 – Inlet	165	25	~580	178	+13	7.9	~1100	≤ 2

The three heating zones reached their corresponding setpoints and remained within a small steady-state error range after stabilization. Zone 1 and Zone 2 presented steady-state errors below or equal to 1,°C, while Zone 3 presented a slightly higher error, below or equal to 2,°C. The highest overshoot was observed in Zone 3, with an estimated value of 13,°C, equivalent to 7.9%. The behavior of the three zones was considered acceptable for the validation because they all reached a stable operation and maintained temperatures suitable for process testing.

3.1.3 Motor Drive Subsystem Results

The motor drive subsystem was validated by testing the extrusion screw motor, the puller motor, and the spooler motor independently. Table 8 present the observed behavior of each motor during the validation tests. The extruder motor required a soft-start ramp to avoid abrupt current peaks at startup, while the puller and spooler motors responded correctly to the RUN/STOP commands generated by the control interface.

TABLE 8
Motor Subsystem Validation Results.

Motor	Function	Observed Behavior	Speed Range	Direction
Extruder (NEMA 23)	Screw drive	Requires soft-start ramp to avoid current peaks; maintains constant rotation during operation.	4–15 RPM	CCW
Puller (NEMA 17)	Filament traction	Responds correctly to RUN/STOP commands; maintains constant speed during pulling.	6–8 RPM	CW
Spooler (NEMA 17)	Filament winding	Speed must vary with spool fill level: 2.65 RPM for an empty spool to 1.26 RPM for a full spool.	1–3 RPM	CW

Note: CW = clockwise rotation; CCW = counterclockwise rotation, defined from the front view of each motor shaft.

The independent validation confirmed that the selected drivers and motor configurations were suitable for the required movements of the prototype. The soft-start ramp implemented for the extrusion motor improved startup behavior and reduced mechanical shock in the screw drive. The puller and spooler motors maintained stable rotation within the required speed ranges, which allowed the system to proceed to integrated extrusion testing.

3.1.4 Communication Subsystem Results

The UART communication interface between the Arduino Nano and the ESP32 was validated through four functional tests covering the main command and telemetry exchange scenarios. The Arduino Nano was used as the HMI controller, while the ESP32 managed the actuator and telemetry side of the system. Table 9 presents the UART frames used during the validation tests and the corresponding system response.

TABLE 9
UART Communication Validation Between Arduino Nano and ESP32.

Test	UART Frame	Observed Response	Result
Start extrusion	RUN=1,MAT=PLA,STATE=PULLING, T1=180.00,T2=190.00, T3=200.00,MENU=2	RUN command was received; the LCD updated the system condition to STATE: RUNNING, and telemetry transmission continued.	Passed
Stop motors	RUN=0,MAT=PLA,STATE=PULLING, T1=180.00,T2=190.00, T3=200.00,MENU=2	The system entered an idle condition and the LCD displayed STATE: IDLE.	Passed
Temperature set-point update	RUN=0,MAT=PETG,STATE=MENU, T1=220.00,T2=230.00, T3=240.00,MENU=0	Material-dependent setpoints were included in the UART frame and temperature feedback continued to be received.	Passed
Status request	RUN=0,MAT=PLA,STATE=INFO, T1=180.00,T2=190.00, T3=200.00,MENU=3	The telemetry frame containing T1,T2,T3,ExtRPM,PullRPM,Diam,Len was parsed and displayed on the INFO screen.	Passed

The communication tests confirmed that the Nano–ESP32 UART link was able to transmit operating commands, material configuration data, and system telemetry. No loss of functionality was observed during the tested cases, and the LCD information was updated according to the received frames.

3.1.5 HMI Validation Results

The HMI was validated by testing six functional features defined in the experimental validation procedure. Table 10 summarizes the expected behavior, observed behavior, and validation status for each feature.

TABLE 10
HMI Functional Validation Results.

Feature	Expected Behavior	Observed Behavior	Status
Menu navigation	Navigate menus with the KY-040 encoder; confirm selection by pressing the encoder button.	Navigation was functional. In some cases, a prolonged press was detected as a double press, producing two buzzer beeps. The navigation flow remained functional.	Passed*
Material selection	Select PLA or PETG; load predefined setpoints and transmit them through UART.	Material selection was correctly loaded; setpoints were transmitted and verified through the ESP32 serial monitor.	Passed
Preheating visualization	Display the three zone temperatures and setpoints during heating.	The preheating screen displayed the three zone temperatures and their corresponding setpoints correctly.	Passed
Pulling control display	Display operating mode and RUN/STOP condition; allow user control from the HMI.	The pulling control screen displayed the operating condition and the RUN/STOP state correctly.	Passed
Auto timeout	Return to the monitoring screen after inactivity without interrupting system operation.	The timeout function was operational. However, after returning from the pulling menu, the encoder was inactive on the INFO screen and required re-entry into the pulling menu.	Passed†
System monitoring	Display temperature, RPM, diameter, length, and system state on the INFO screen.	The INFO screen displayed all monitoring variables received from the ESP32 correctly.	Passed

* *Minor encoder debounce issue; it did not affect the overall navigation flow.*

† *Firmware navigation limitation identified after auto-timeout return.*

The HMI tests confirmed that the user interface provided the required interaction functions for menu navigation, material selection, preheating monitoring, pulling control, and system visualization. The identified limitations were related to firmware behavior rather than hardware failure, and therefore they can be corrected through debounce adjustment and navigation-state refinement.

3.1.6 Extrusion Process Results

Before conducting the final extrusion trials, two screw configurations were evaluated. The first configuration used a wood drill bit as the material transport element. This configuration was able to convey the PLA pellets along the barrel and promote material melting; however, it

did not generate continuous extrusion at the nozzle outlet. This limitation was attributed mainly to the absence of a defined compression section in the screw geometry and, possibly, to an inadequate nozzle geometry for pressure build-up and stable material discharge.

A second configuration was then implemented using the imported screw. During the initial tests with this configuration, the barrel rotated together with the screw because the softened plastic adhered to the internal wall of the barrel, transmitting torque to the barrel assembly. This problem was solved by installing a 1/4 in set screw on the aluminum support, which mechanically locked the barrel and prevented co-rotation. After this correction, the screw was able to transport, melt, pressurize, and extrude the PLA material through the nozzle.

The final extrusion trials were conducted using a 60/40 blend of virgin and recycled PLA material, with 50,g of material per batch. The thermal setpoints were fixed across all trials at Zone 1 = 230,°C, Zone 2 = 200,°C, and Zone 3 = 190,°C. The screw speed was varied between trials in order to evaluate its effect on the resulting filament diameter.

For each trial, 28 diameter measurements were taken along an 800,cm filament sample at approximately 30,cm intervals, including the final point at 800,cm. A digital caliper was used to record two perpendicular diameters, D1 and D2, at each measurement point. The average diameter at each point was calculated as shown in Equation 3.1.

$$d_{avg} = \frac{D1 + D2}{2} \quad (3.1)$$

The mean diameter, standard deviation, and percentage error with respect to the 1.75,mm target diameter were calculated for each trial. The percentage error was computed according to Equation 3.2.

$$Error, (\%) = \frac{|\bar{d} - 1.75|}{1.75} \times 100 \quad (3.2)$$

Table 11 presents the summary of the ten extrusion trials. The complete measurement dataset is provided in Appendix B.

TABLE 11
Extrusion Trial Summary: Effect of Screw Speed on Filament Diameter.

Trial	Speed (RPM)	T1 (°C)	T2 (°C)	T3 (°C)	Length (cm)	<i>N</i>	$\bar{d}$ (mm)	σ (mm)	Error (%)
1	15	230	200	190	800	28	0.92	0.39	47.43
2	10	230	200	190	800	28	1.07	0.18	38.86
3	9	230	200	190	800	28	1.09	0.18	37.71
4	8	230	200	190	800	28	1.13	0.14	35.43
5	7	230	200	190	800	28	1.15	0.19	34.29
6	6	230	200	190	800	28	1.18	0.19	32.57
7	6	230	200	190	800	28	1.18	0.19	32.57
8	5	230	200	190	800	28	1.13	0.19	35.43
9	5	230	200	190	800	28	1.14	0.19	34.86
10	4	230	200	190	800	28	1.05	0.18	40.00

Note: T1 = Zone 1 (Nozzle); T2 = Zone 2 (Center); T3 = Zone 3 (Inlet). Target diameter: 1.75 mm.

The results show that the prototype was able to produce continuous PLA filament after the mechanical correction of the barrel support. However, the resulting diameters remained below the target value of 1.75,mm. The highest mean diameter was obtained in Trials 6 and 7 at 6,RPM, where the average diameter reached 1.18,mm with a standard deviation of 0.19,mm and an error of 32.57%. The lowest error was therefore obtained near 6,RPM, while higher and lower screw speeds produced smaller average diameters.

3.2 Discussion

3.2.1 Prototype Integration and Mechanical Corrections

The assembled prototype demonstrated that the mechanical, electrical, and control sub-systems could be integrated into a functional filament extrusion and recycling system. The modular frame allowed the extrusion tower, puller, spooler, and HMI enclosure to be organized in a compact configuration suitable for laboratory testing.

One of the most relevant findings during the mechanical validation stage was the difference in performance between the two screw configurations in terms of performance. The wood drill bit configuration was able to transport and melt the material, but it did not provide the

required compression and pressure generation for continuous extrusion. the result confirmed that material melting is not sufficient for filament production. In a single-screw extrusion process, the screw geometry has also to be capable of providing progressive material transport, compaction, and pressure build-up towards the nozzle.

The imported screw was more efficient as its geometry was more suitable to handle material transport and pressurization. But, the first tests with this screw revealed a mechanical limitation: the barrel rotated along with the screw due to adhesion between the softened PLA and the internal barrel wall. This condition reduced the relative motion required for material transport and prevented stable extrusion. The installation of the 1/4 in set screw worked as an anti-rotation constraint so that the barrel remained fixed while the screw rotated. This correction was essential to allow a successful extrusion.

3.2.2 Thermal Control Performance

The validation results of the PID show that the thermal subsystem was able to achieve the stable closed loop operation in the three heating zones. The steady-state error was maintained in a small band, less than or equal to 1°C in Zones 1 and 2 and less than or equal to 2°C in Zone 3. These values are acceptable for the prototype validation stage since the temperature was stable enough after the transient response.

Zone 3 presented the highest overshoot and the longest settling time. This behavior may be related to the thermal distribution along the barrel, the location of the heater block, the sensor position, and the heat transfer conditions at the inlet section. Although this response did not prevent stable operation, it suggests that further PID tuning or thermal insulation could improve the uniformity of the heating process.

It is worth mentioning that the PID validation and extrusion trials were separate experiments. The results of the PID show that the control loop can reach and maintain chosen setpoints. For material processing the extrusion trials have chosen a different temperature profile. This separation is important as the PID tests are testing control performance, while the extrusion tests are testing the combined effect of temperature, screw speed, material behavior, nozzle geometry, and pulling conditions.

3.2.3 Motor Drive Performance

The results from the motor validation test demonstrated that the chosen motor-drivers combinations met the needs of the prototype. The NEMA 23 motor together with the gear box generated the necessary torque for rotating the extruder screw, whereas the NEMA 17 motors

allowed separate control over the puller and spooler systems.

One significant operational finding was the necessity for a soft-start ramp on the extruder motor. The screw drive may be exposed to abrupt current peaks and mechanical stress at startup, without gradual acceleration, especially if material is present inside the heated barrel. Thus, the ramp increased the reliability of the system and reduced the risk of abrupt load variations.

The puller and spooler motors responded correctly to RUN/STOP commands, which is essential for process control. However, the spooler speed must be adjusted according to the spool fill level. As the spool diameter increases, the angular velocity must decrease to maintain a more uniform winding speed. This behavior should be considered in future firmware iterations to improve filament collection and prevent excessive pulling force.

3.2.4 Communication and HMI Performance

The UART validation demonstrated that the Arduino Nano and ESP32 were able to exchange operating states, material information, temperature data, motor information, and monitoring variables. This result confirms that the selected two-microcontroller architecture was suitable for the prototype.

The HMI validation demonstrated that the LCD and KY-040 encoder offer the necessary user interaction for menu navigation, material selection, preheating monitoring, pulling control and system monitoring. The issues found were minor and mostly related to the behavior of the firmware. Double detection of a long encoder press. This shows the debounce logic needs to be improved. Similarly, the encoder inactivity after returning to the INFO screen suggests that the menu state machine should be refined after timeout events.

Despite these limitations, the HMI remained functional and did not interrupt the main operation of the system. So, the interface can be considered valid for prototype-level operation, while future improvements should focus on firmware robustness and user interaction stability.

3.2.5 Extrusion Performance and Diameter Evaluation

The extrusion trials confirmed that the final mechanical configuration was capable of producing continuous PLA filament. However, the measured diameters remained below the target diameter of 1.75mm. This result indicates that the prototype achieved functional extrusion, but it did not yet meet the dimensional requirements of commercial FDM filament.

The effect of screw speed showed a clear trend. At 15 RPM, the mean diameter was 0.92 mm and the standard deviation was 0.39 mm, indicating unstable filament formation and

high diameter variability. As the screw speed decreased from 15 RPM to 6 RPM, the mean diameter increased progressively from 0.92 mm to 1.18 mm. This suggests that lower screw speeds allowed more stable material transport and improved pressure generation inside the barrel.

The best results were obtained at 6,RPM, where two repeated trials produced the same mean diameter of 1.18 mm and the same percentage error of 32.57%. This repeatability suggests that 6 RPM was the most favorable operating point between the tested conditions. However, when the screw speed was reduced below this value, the average diameter decreased again, reaching 1.13-1.14 mm at 5 RPM and 1.05 mm at 4 RPM. Therefore, reducing the screw speed alone was not sufficient to reach the target diameter.

The fact that all measured diameters were below 1.75 mm suggests that the final filament size was affected not only by screw speed, but also by the relationship between extrusion flow rate, temperature and pulling speed. If the puller speed is too high compared with the material flow rate at the nozzle, the extruded filament is stretched, reducing the final diameter. Nozzle geometry, cooling distance, material viscosity, and pressure generation inside the barrel may also have contributed to the reduced diameter.

Trial 4 at 8,RPM presented the lowest standard deviation, with $\sigma = 0.14$ mm, but its mean diameter was only 1.13 mm. This indicates that dimensional stability and target accuracy are different performance criteria. A trial may produce a relatively uniform filament while still being far from the required 1.75 mm diameter. For this reason, future optimization must consider both the mean diameter and the standard deviation.

3.2.6 Limitations and Future Improvements

The main limitation of the prototype was the inability to reach the commercial target diameter of 1.75 mm during the final extrusion trials. Although continuous extrusion was achieved, the resulting filament diameter remained between 0.92 mm and 1.18 mm on average, depending on the screw speed. This confirms that the system requires further optimization before producing filament suitable for standard FDM printers.

Future improvements should focus on the relationship between material flow rate, temperature and pulling speed. The puller speed should be reduced according to the measured filament diameter in order to prevent excessive stretching of the extruded material. In addition, the thermal profile should be optimized specifically for the final screw and barrel geometry, rather than only for general PLA melting conditions.

Overall, the results demonstrate that the developed prototype successfully integrated the required mechanical, thermal, electronic, communication, and HMI subsystems. The system achieved material transport, melting, and extrusion after correcting the barrel co-rotation problem. However, the extrusion process still requires optimization to reach the target filament diameter and improve dimensional stability.

Chapter IV

Conclusions and Recommendations

4.1 Conclusions

Regarding the thermomechanical sizing of the extrusion assembly, a single-screw geometry with an 18.00 mm outer diameter, 18.00 mm pitch, 250mm functional length, and 3:1 compression ratio was defined and implemented, yielding a theoretical drag flow of 11,220 mm³/min at 20 RPM and a diametral clearance of 0.22 mm.

Regarding the development of the powertrain for high-viscosity materials, the NEMA 23 motor with a 15.3:1 planetary gearbox delivered an estimated 15.5 Nm output torque, exceeding the 6.48 Nm minimum requirement and achieving a mechanical safety factor of 2.39.

Regarding the implementation of the electronic control system, three independent PID loops maintained steady-state thermal errors at or below 2°C; the UART link between the ESP32 and Arduino Nano was validated across four test cases; and the HMI was validated across six functional features, with identified firmware limitations not affecting system operation.

Regarding the experimental validation under laboratory conditions, ten extrusion trials with a 60/40 virgin/recycled PLA mix produced continuous filament, reaching a maximum mean diameter of 1.18mm at 6RPM (error: 32.57%), confirming operational feasibility but requiring further optimization to achieve the 1.75mm target.

4.2 Recommendations

The thermal profile across the three heating zones should be refined for the final screw and barrel geometry, and additional PID tuning with barrel insulation should be evaluated to reduce Zone 3 overshoot and improve melt homogeneity.

The HMI firmware should be updated to correct the encoder debounce limitation and the navigation state inconsistency that occurs after automatic timeout events.

The spooler motor speed should incorporate a dynamic compensation mechanism to reduce angular velocity proportionally as spool diameter increases during filament collection.

The barrel anti-rotation constraint should be replaced with a permanent keyed or flanged fixture to improve structural stability and reduce displacement risk during extended extrusion cycles.

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Appendix A – Bill of Materials

TABLE A.1

Bill of Materials for the Filament Extrusion System Prototype.

No.	Item	Qty.	Unit Price (USD)	Total (USD)
1	NEMA 23 stepper motor with 15:1 planetary gearbox	1	72.99	72.99
2	50 W cartridge heater and thermistor set	3	4.66	13.99
3	LCD 20×4 character display	1	5.68	5.68
4	Electrical connection terminals	43	0.14	5.81
5	Filament extruder puller kit	1	6.38	6.38
6	DM542 stepper motor driver	1	12.93	12.93
7	Bearings 608 and 625, assorted	8	1.08	8.60
8	Stainless steel tube	1	2.10	2.10
9	Kiwy drill bit screw	1	14.89	14.89
10	1-1/4 in aluminum shaft	1	1.59	1.59
11	9 mm aluminum plate, 170×250 mm	1	17.85	17.85
12	Lathe machining service	1	35.00	35.00
13	Oxyfuel cutting service	1	30.00	30.00
14	KY-040 rotary encoder	1	2.50	2.50
15	Logic level converter module	1	1.90	1.90
16	UGN3503 linear Hall effect sensor	1	1.25	1.25
17	IRFZ44N power MOSFET	3	0.86	2.58
18	16-pin DIP IC socket	1	0.16	0.16
19	ULN2003A Darlington transistor array	1	0.89	0.89
20	Screw, barrel, and nozzle assembly	1	244.55	244.55
Total prototype cost				481.64

Appendix B – Complete Filament Diameter Measurement Data

Tables B.1 through B.10 present the complete filament diameter measurements for all ten extrusion trials. At each measurement point, two perpendicular diameters $D1$ and $D2$ were recorded using a digital caliper, and the point average was computed as $d_{avg} = (D1 + D2)/2$. Measurements were taken approximately every 30 cm along each 800 cm filament sample, including the final point at 800 cm, yielding 28 measurement points per trial.

TABLE B.1
Diameter Measurements for Trial 1 at 15 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.82	1.90	1.86
P2	30	1.33	1.29	1.31
P3	60	0.84	0.90	0.87
P4	90	0.73	0.74	0.74
P5	120	1.06	1.20	1.13
P6	150	1.00	1.00	1.00
P7	180	1.15	1.03	1.09
P8	210	1.55	1.66	1.61
P9	240	0.58	0.57	0.57
P10	270	0.59	0.54	0.56
P11	300	0.60	0.60	0.60
P12	330	0.50	0.52	0.51
P13	360	1.44	1.39	1.42
P14	390	0.65	0.66	0.66
P15	420	0.65	0.67	0.66
P16	450	0.61	0.64	0.63
P17	480	0.65	0.68	0.67
P18	510	0.54	0.56	0.55
P19	540	0.62	0.64	0.63
P20	570	0.61	0.63	0.62
P21	600	0.67	0.66	0.67
P22	630	0.73	0.79	0.76
P23	660	0.69	0.71	0.70
P24	690	0.55	0.63	0.59
P25	720	1.30	1.41	1.36
P26	750	0.90	0.97	0.94
P27	780	1.68	1.66	1.67
P28	800	1.35	1.43	1.39
Mean $\bar{d}$				0.92
Std. Dev. σ				0.39

TABLE B.2
Diameter Measurements for Trial 2 at 10 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.01	1.05	1.03
P2	30	1.03	1.03	1.03
P3	60	0.92	0.91	0.92
P4	90	0.88	0.90	0.89
P5	120	0.91	0.90	0.91
P6	150	1.27	1.30	1.29
P7	180	0.86	0.88	0.87
P8	210	0.86	0.86	0.86
P9	240	1.14	1.12	1.13
P10	270	1.34	1.33	1.34
P11	300	1.00	0.98	0.99
P12	330	1.06	1.08	1.07
P13	360	1.34	1.36	1.35
P14	390	1.09	1.10	1.10
P15	420	1.26	1.27	1.27
P16	450	1.23	1.23	1.23
P17	480	0.90	0.91	0.91
P18	510	0.70	0.72	0.71
P19	540	0.84	0.83	0.84
P20	570	0.95	0.96	0.96
P21	600	0.99	1.00	1.00
P22	630	1.02	1.02	1.02
P23	660	0.98	1.00	0.99
P24	690	1.21	1.20	1.21
P25	720	1.24	1.22	1.23
P26	750	1.24	1.25	1.25
P27	780	1.27	1.30	1.29
P28	800	1.35	1.32	1.34
Mean $\bar{d}$				1.07
Std. Dev. σ				0.18

TABLE B.3
Diameter Measurements for Trial 3 at 9 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.04	1.03	1.04
P2	30	1.03	1.03	1.03
P3	60	0.96	0.94	0.95
P4	90	0.93	0.89	0.91
P5	120	0.92	0.88	0.90
P6	150	1.27	1.32	1.30
P7	180	0.84	0.88	0.86
P8	210	0.89	0.88	0.89
P9	240	1.14	1.15	1.15
P10	270	1.38	1.31	1.35
P11	300	1.04	1.02	1.03
P12	330	1.07	1.07	1.07
P13	360	1.40	1.37	1.39
P14	390	1.08	1.09	1.09
P15	420	1.31	1.30	1.31
P16	450	1.27	1.27	1.27
P17	480	0.92	0.97	0.95
P18	510	0.71	0.74	0.73
P19	540	0.89	0.86	0.88
P20	570	1.00	0.99	1.00
P21	600	1.03	0.98	1.00
P22	630	1.02	1.02	1.02
P23	660	0.97	1.00	0.99
P24	690	1.20	1.20	1.20
P25	720	1.27	1.23	1.25
P26	750	1.25	1.25	1.25
P27	780	1.27	1.35	1.31
P28	800	1.38	1.35	1.37
Mean $\bar{d}$				1.09
Std. Dev. σ				0.18

TABLE B.4
Diameter Measurements for Trial 4 at 8 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.04	1.10	1.07
P2	30	0.93	0.96	0.95
P3	60	1.12	1.07	1.10
P4	90	1.23	1.26	1.25
P5	120	1.26	1.25	1.25
P6	150	1.15	1.16	1.15
P7	180	0.96	0.95	0.96
P8	210	0.91	0.98	0.95
P9	240	1.14	1.08	1.11
P10	270	1.30	1.28	1.29
P11	300	1.20	1.16	1.18
P12	330	1.08	1.10	1.09
P13	360	1.29	1.26	1.27
P14	390	1.28	1.32	1.30
P15	420	1.19	1.17	1.18
P16	450	1.36	1.34	1.35
P17	480	0.95	0.94	0.95
P18	510	0.81	0.88	0.85
P19	540	0.97	0.93	0.95
P20	570	0.95	0.99	0.97
P21	600	1.14	1.10	1.12
P22	630	1.26	1.25	1.25
P23	660	1.01	1.07	1.04
P24	690	1.16	1.16	1.16
P25	720	1.23	1.25	1.24
P26	750	1.03	1.08	1.06
P27	780	1.32	1.39	1.36
P28	800	1.21	1.15	1.18
Mean $\bar{d}$				1.13
Std. Dev. σ				0.14

TABLE B.5
Diameter Measurements for Trial 5 at 7 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.10	1.05	1.08
P2	30	0.89	0.91	0.90
P3	60	1.19	1.19	1.19
P4	90	1.56	1.54	1.55
P5	120	1.55	1.52	1.54
P6	150	1.06	1.06	1.06
P7	180	1.01	1.02	1.02
P8	210	0.93	1.02	0.98
P9	240	1.08	1.06	1.07
P10	270	1.18	1.17	1.17
P11	300	1.34	1.35	1.35
P12	330	1.08	1.13	1.11
P13	360	1.17	1.19	1.18
P14	390	1.45	1.41	1.43
P15	420	1.11	1.08	1.10
P16	450	1.37	1.44	1.41
P17	480	1.02	0.99	1.00
P18	510	0.96	1.01	0.99
P19	540	1.01	0.99	1.00
P20	570	1.02	1.01	1.02
P21	600	1.18	1.16	1.17
P22	630	1.36	1.38	1.37
P23	660	1.08	1.08	1.08
P24	690	1.03	1.06	1.05
P25	720	1.19	1.24	1.21
P26	750	0.84	0.92	0.88
P27	780	1.38	1.34	1.36
P28	800	0.95	1.00	0.98
Mean $\bar{d}$				1.15
Std. Dev. σ				0.18

TABLE B.6
Diameter Measurements for Trial 6 at 6 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.13	1.11	1.12
P2	30	0.89	0.91	0.90
P3	60	1.24	1.21	1.23
P4	90	1.58	1.60	1.59
P5	120	1.56	1.55	1.56
P6	150	1.07	1.09	1.08
P7	180	1.08	1.06	1.07
P8	210	1.00	1.02	1.01
P9	240	1.08	1.06	1.07
P10	270	1.23	1.24	1.24
P11	300	1.34	1.34	1.34
P12	330	1.14	1.16	1.15
P13	360	1.23	1.20	1.22
P14	390	1.46	1.47	1.47
P15	420	1.14	1.11	1.13
P16	450	1.42	1.44	1.43
P17	480	1.06	1.04	1.05
P18	510	0.99	1.02	1.01
P19	540	1.06	1.04	1.05
P20	570	1.01	1.03	1.02
P21	600	1.21	1.19	1.20
P22	630	1.42	1.43	1.43
P23	660	1.12	1.10	1.11
P24	690	1.08	1.11	1.10
P25	720	1.25	1.26	1.26
P26	750	0.89	0.92	0.91
P27	780	1.38	1.40	1.39
P28	800	1.00	1.02	1.01
Mean $\bar{d}$				1.18
Std. Dev. σ				0.19

TABLE B.7
Diameter Measurements for Trial 7 at 6 RPM, repeated.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.11	1.08	1.10
P2	30	0.92	0.92	0.92
P3	60	1.24	1.23	1.23
P4	90	1.60	1.58	1.59
P5	120	1.53	1.54	1.54
P6	150	1.06	1.09	1.08
P7	180	1.10	1.07	1.09
P8	210	1.04	0.99	1.02
P9	240	1.07	1.05	1.06
P10	270	1.26	1.22	1.24
P11	300	1.32	1.34	1.33
P12	330	1.13	1.14	1.13
P13	360	1.21	1.23	1.22
P14	390	1.46	1.50	1.48
P15	420	1.14	1.07	1.11
P16	450	1.46	1.47	1.47
P17	480	1.10	1.07	1.09
P18	510	1.02	0.99	1.00
P19	540	1.06	1.02	1.04
P20	570	1.00	0.99	1.00
P21	600	1.20	1.23	1.21
P22	630	1.40	1.45	1.42
P23	660	1.12	1.09	1.11
P24	690	1.12	1.15	1.14
P25	720	1.25	1.28	1.27
P26	750	0.86	0.90	0.88
P27	780	1.42	1.41	1.42
P28	800	1.00	1.04	1.02
Mean $\bar{d}$				1.18
Std. Dev. σ				0.19

TABLE B.8
Diameter Measurements for Trial 8 at 5 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.04	1.07	1.06
P2	30	0.84	0.89	0.87
P3	60	1.16	1.20	1.18
P4	90	1.50	1.52	1.51
P5	120	1.52	1.51	1.52
P6	150	1.00	1.01	1.00
P7	180	1.06	0.99	1.02
P8	210	0.96	0.98	0.97
P9	240	1.02	1.02	1.02
P10	270	1.18	1.22	1.20
P11	300	1.27	1.31	1.29
P12	330	1.07	1.10	1.09
P13	360	1.19	1.13	1.16
P14	390	1.40	1.44	1.42
P15	420	1.06	1.06	1.06
P16	450	1.41	1.43	1.42
P17	480	0.98	0.97	0.98
P18	510	0.92	1.00	0.96
P19	540	1.04	1.02	1.03
P20	570	0.95	0.95	0.95
P21	600	1.19	1.16	1.17
P22	630	1.38	1.42	1.40
P23	660	1.08	1.01	1.05
P24	690	1.06	1.04	1.05
P25	720	1.21	1.25	1.23
P26	750	0.81	0.84	0.83
P27	780	1.30	1.35	1.33
P28	800	0.93	0.98	0.96
Mean $\bar{d}$				1.13
Std. Dev. σ				0.19

TABLE B.9
Diameter Measurements for Trial 9 at 5 RPM, repeated.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	1.06	1.05	1.06
P2	30	0.88	0.90	0.89
P3	60	1.19	1.26	1.23
P4	90	1.53	1.49	1.51
P5	120	1.48	1.46	1.47
P6	150	0.93	1.00	0.97
P7	180	1.07	0.97	1.02
P8	210	1.01	1.01	1.01
P9	240	1.04	1.01	1.02
P10	270	1.15	1.25	1.20
P11	300	1.27	1.28	1.27
P12	330	1.07	1.08	1.08
P13	360	1.16	1.10	1.13
P14	390	1.41	1.50	1.46
P15	420	1.11	1.12	1.12
P16	450	1.44	1.41	1.42
P17	480	0.93	0.91	0.92
P18	510	0.91	1.00	0.96
P19	540	1.03	1.03	1.03
P20	570	0.95	1.01	0.98
P21	600	1.25	1.23	1.24
P22	630	1.40	1.45	1.42
P23	660	1.01	1.00	1.00
P24	690	1.02	1.04	1.03
P25	720	1.23	1.28	1.25
P26	750	0.87	0.85	0.86
P27	780	1.35	1.35	1.35
P28	800	0.96	1.01	0.99
Mean $\bar{d}$				1.14
Std. Dev. σ				0.19

TABLE B.10
Diameter Measurements for Trial 10 at 4 RPM.

Point	Dist. (cm)	D1 (mm)	D2 (mm)	Avg. (mm)
P1	0	0.97	1.06	1.02
P2	30	1.01	0.99	1.00
P3	60	0.92	0.87	0.90
P4	90	0.82	0.86	0.84
P5	120	0.88	0.91	0.90
P6	150	1.29	1.26	1.27
P7	180	0.85	0.85	0.85
P8	210	0.88	0.84	0.86
P9	240	1.16	1.07	1.12
P10	270	1.36	1.28	1.32
P11	300	1.02	0.94	0.98
P12	330	1.01	1.05	1.03
P13	360	1.34	1.33	1.34
P14	390	1.08	1.08	1.08
P15	420	1.23	1.26	1.25
P16	450	1.19	1.23	1.21
P17	480	0.84	0.92	0.88
P18	510	0.68	0.72	0.70
P19	540	0.84	0.82	0.83
P20	570	0.92	0.91	0.92
P21	600	0.98	0.97	0.98
P22	630	0.99	1.03	1.01
P23	660	0.98	0.96	0.97
P24	690	1.17	1.17	1.17
P25	720	1.21	1.18	1.19
P26	750	1.19	1.22	1.21
P27	780	1.29	1.29	1.29
P28	800	1.36	1.31	1.34
Mean $\bar{d}$				1.05
Std. Dev. σ				0.18