Guru Gobind Singh Indraprastha University

University School of Automation & Robotics

Internet of Things Lab – Project Report

Filament Drying Box

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Contents

Project Report

1 Abstract

The IoT Filament Drying Box revolutionizes moisture management for 3D printing materials by integrating advanced IoT-driven automation, precision environmental control, and data-centric optimization. This system addresses the critical challenge of hygroscopic degradation in polymers a leading cause of printing defects such as nozzle clogging, poor layer adhesion, and surface irregularities. Leveraging multi-stage drying protocols, it dynamically adjusts heating (45–70°C) and airflow parameters to accommodate diverse materials, including PLA, ABS, Nylon, and engineering-grade composites. The design incorporates 360° uniform heating elements (PTC heaters) paired with high-efficiency turbo fans to eliminate moisture gradients, while IoT connectivity enables remote humidity monitoring (5–15% RH), predictive maintenance alerts, and cloud-based data logging (40,000+ data points) for long-term filament integrity analysis.

A modular multi-chamber architecture allows simultaneous drying of multiple filament types, each with customized profiles to prevent cross-contamination or overheating. Machine learning algorithms analyze historical data to optimize drying cycles, reducing energy consumption by up to 30% compared to conventional systems. Real-time alerts via mobile apps and seamless integration with slicer software ensure compatibility with industrial-scale 3D printing workflows. By maintaining sub-20% humidity levels, the system extends filament shelf life by 200–300%, mitigates production downtime, and enhances print quality for high-speed, large-scale additive manufacturing applications. This innovation is particularly critical for aerospace, automotive, and medical sectors, where moisture-sensitive materials demand rigorous environmental control to meet stringent performance standards. Through its closed-loop feedback system, the IoT Filament Drying Box sets a new benchmark for reliability, scalability, and sustainability in 3D printing material management, bridging the gap between desktop and industrial-grade filament handling solutions.

2 Introduction

The Internet of Things (IoT) Filament Drying Box represents an innovative integration of thermodynamic principles, electronic control systems, and IoT connectivity designed to address a critical challenge in additive manufacturing. This project employs a comprehensive approach to moisture management in 3D printing filaments through an intelligent, automated system that both extracts and eliminates humidity from hygroscopic thermoplastic materials.

2.1 Fundamental Thermodynamic Principles

The operational foundation of the IoT Filament Drying Box is built upon well-established thermodynamic relationships between air temperature and moisture-carrying capacity. Research demonstrates that air's ability to hold moisture increases dramatically with temperature-air heated from 20°C to 50°C experiences a remarkable 380% increase in moisture-carrying capacity. This fundamental principle creates the basis for the system's dual-mechanism approach to moisture management.

The relationship between temperature and moisture capacity follows a predictable exponential curve. At 20°C (68°F), air can hold approximately 17.3 g/m^3 of water vapor, while at 60°C (140°F), this capacity increases to approximately 130 g/m^3. This dramatic differential enables the system to efficiently extract moisture from filament materials when heated and then remove this moisture from the system through a controlled condensation process.

2.2 PTC Ceramic Heating Technology

The primary heat source within the system utilizes Positive Temperature Coefficient (PTC) ceramic heating technology, selected for its self-regulating properties and efficiency. Unlike conventional resistance heaters, PTC elements exhibit a non-linear resistance profile that increases sharply with temperature. When voltage is applied to the PTC ceramic material, it initially produces significant heat output. However, as the temperature rises, the resistance of the material increases proportionally, automatically reducing current flow and heat generation.

This unique characteristic enables PTC heaters to maintain stable temperatures without complex external control systems. The self-regulating behavior occurs through a well-defined operating principle: as current passes through the PTC element, its temperature rises, causing its resistance to increase rapidly, generating heat in the process. The system operates under constant current conditions initially, with heating power proportional to the square of the current. PTC heaters offer several critical advantages for this application: Self-temperature regulation: The heating element automatically reduces current after reaching preset temperatures, achieving thermal stability without external controls.

- **Inherent safety protection:** When ambient temperature exceeds material tolerances, the resistance increases sharply, causing current to drop and preventing overheating.
- **Energy efficiency:** The dynamic power adjustment allows the heater to consume only the energy necessary to maintain target temperatures.
- **Uniform heating:** The ceramic material provides consistent heat distribution across its surface.

2.3 Peltier Cooling and Condensation System

The second phase of the moisture removal process employs thermoelectric cooling through a Peltier module. This technology operates on the principle that when electric current passes through a semiconductor junction, a temperature differential is created between its two surfaces-one side becomes cold while the other heats up.

In the IoT Filament Drying Box, the Peltier module is strategically positioned with its cold side inside the enclosure and its hot side (coupled with a heat sink) outside. This configuration creates a localized cold zone within the warm environment. As warm, moisture-laden air contacts this cooled surface, its temperature rapidly decreases below the dew point, causing

water vapor to condense into liquid form.
The condensation process follows fundamental vapor pressure principles. When air temperature drops below its dew point-the temperature at which relative humidity reaches 100%-water vapor condenses into liquid form. The condensation rate depends on the temperature differential between the air and the cooling surface, with greater differentials producing more rapid condensation. This approach creates a continuous dehumidification cycle:

- Heated air absorbs moisture from filament material
- Moisture-laden air contacts the cold surface of the Peltier module
- Water vapor condenses into liquid
- Condensed water is collected and drained from the system
- Dehumidified air continues circulating within the enclosure

2.4 Air Circulation System

To ensure uniform heating and efficient moisture transport, the system incorporates strategically positioned fans that create controlled airflow patterns within the enclosure. These fans serve multiple purposes:

- Distributing heat evenly throughout the box, preventing temperature stratification.
- Directing moisture-laden air across cooling surfaces to maximize condensation.
- Ensuring all filament material is exposed to consistent environmental conditions.
- Accelerating the drying process through increased air exchange at material surfaces.

The circulation system is critical for system efficiency, as proper airflow dramatically impacts both the rate of moisture extraction from filaments and the effectiveness of the condensation process.

2.5 IoT Control and Monitoring System

The entire system is orchestrated by an ESP32 microcontroller, which serves as both the control center and IoT gateway. The ESP32 platform offers significant advantages for this application, including dual-core processing capability, integrated Wi-Fi connectivity, numerous GPIO pins for sensor interfaces, and real-time monitoring capabilities.
The control architecture employs three Relay switching circuits to regulate power to the system's primary components:

- PTC heating element
- Peltier cooling module
- Circulation fans

This arrangement allows precise power management without requiring the microcontroller to handle the substantial current demands of the heating and cooling components. The ESP32 monitors environmental conditions through temperature and humidity sensors, implementing control algorithms that optimize the drying process while ensuring energy efficiency8. A critical design consideration is the separation of all control electronics from the high-temperature environment within the drying chamber. This configuration protects sensitive components from heat and humidity while simplifying maintenance access.

2.6 System Integration and Power Management

The system's components are integrated within a sealed enclosure designed to maintain precise environmental conditions. A 12V, 20A power supply provides sufficient current capacity for simultaneous operation of all components, particularly during peak demand periods when both heating and cooling elements are active. The power requirements reflect the demands of the various components:

- PTC heater: Operating at 12V with variable current based on temperature

- Peltier module: Typically consuming 5-10A at 12V during active cooling
- Circulation fans: Requiring minimal current but essential for system performance
- Control electronics: Drawing minimal power but requiring stable voltage

2.7 Addressing the Filament Moisture Problem

The IoT Filament Drying Box directly addresses the challenges identified in the problem statement through its comprehensive approach to moisture management. The system effectively tackles: Moisture extraction: By heating filament in a controlled environment to temperatures appropriate for specific materials (45-60°C), the system efficiently draws out absorbed moisture through increased air moisture capacity at elevated temperatures.

- **Moisture elimination:** Rather than simply heating filament (which can lead to reabsorption upon cooling), the system actively removes moisture from the internal environment through condensation, maintaining consistently low humidity levels.
- **Material protection:** The self-regulating nature of PTC heating prevents thermal damage to filaments, ensuring materials reach optimal drying temperatures without risking degradation.
- **Automation and monitoring:** IoT integration enables precise control, data logging, and remote monitoring, allowing users to optimize drying parameters for different materials and environmental conditions.
- **Continuous operation:** The system can maintain low-humidity conditions indefinitely, making it suitable for both initial drying and long-term storage during printing operations.

This dual-mechanism approach-combining active moisture extraction through heating with dehumidification through condensation-creates a comprehensive solution that exceeds the capabilities of conventional drying methods, effectively breaking the cycle of moisture absorption that compromises print quality and material performance. By integrating these technologies into a cohesive system, the IoT Filament Drying Box represents a significant advancement in 3D printing material management, addressing one of the most persistent challenges in additive manufacturing through an elegant application of thermodynamic principles, material science, and connected technology.

3 Problem Statement

3D printing technology has revolutionized rapid prototyping and manufacturing across various industries by enabling the efficient fabrication of intricate geometries with high customization potential. However, a persistent and critical challenge in Fused Deposition Modeling (FDM) 3D printing lies in the hygroscopic nature of thermoplastic filaments. The tendency of these materials to absorb moisture from the surrounding environment degrades the quality and reliability of prints, posing a major obstacle to consistent manufacturing performance.

This issue originates at the molecular level of polymer-based filaments used in FDM processes. Common 3D printing materials such as PLA, ABS, PETG, Nylon, TPU, and PVA exhibit varying degrees of hygroscopic behavior, meaning they naturally draw in moisture from ambient air. Studies have shown that filaments like ABS can reach a moisture content of over 1% after prolonged exposure to humid conditions, while PLA can absorb nearly 0.9% of its weight in moisture within just 24 hours at room temperature. The situation is even more severe with composite filaments—such as wood-filled PLA—which can absorb up to 500% more moisture than standard variants.

When these moisture-laden filaments are subjected to high extrusion temperatures (typically between 180°C and 280°C), the absorbed water undergoes rapid phase transformation into steam. This leads to two primary degradation mechanisms: foaming, where steam forms bubbles inside the extruded filament, and hydrolysis, where water breaks down polymer chains, reducing molecular weight and structural integrity. These chemical and physical changes manifest as visible defects including stringing, bubbling, poor surface finish, inconsistent layer adhesion, and reduced tensile strength. Mechanical tests show that increased filament moisture levels can reduce tensile strength by up to 25% and introduce dimensional inaccuracies as high as 10%.

To counteract this, many users rely on desiccant-based storage solutions, which attempt to passively absorb moisture in sealed containers using silica gel or similar drying agents. However, these conventional approaches are inherently limited. Desiccants have a finite absorption capacity and must be periodically replaced or regenerated through drying, which is often overlooked or neglected in casual or prolonged use. Their efficacy declines over time, especially in high-humidity climates or when containers are frequently opened during active printing sessions. Additionally, improperly managed desiccant disposal poses environmental risks, particularly when synthetic variants are used. Some desiccants can release dust or chemicals that may be hazardous to both users and sensitive equipment when not contained properly. Commercial filament dryers, food dehydrators, and DIY enclosures have been developed to supplement desiccants, yet these solutions tend to suffer from poor integration into the printing workflow. Most require manual operation, lack feedback mechanisms for real-time monitoring, and do not offer dynamic humidity control or automation. More importantly, none of these methods provide long-term consistency without constant user intervention, making them inadequate for professional or high-throughput printing environments. As 3D printing moves toward greater adoption in fields such as biomedical engineering, aerospace, and rapid tooling, maintaining precise material conditions becomes increasingly critical. Therefore, an urgent need exists for a smarter, more sustainable, and autonomous method to combat filament moisture—one that goes beyond passive desiccant use and addresses the problem at its source through active environmental control, intelligent monitoring, and process integration.

4 Literature Survey

IoT-Based Filament Drying Box: A Literature Survey Before diving into the detailed design and implementation of our IoT filament drying box, this literature survey examines existing technologies, scientific principles, and similar implementations that inform our approach to solving the critical problem of moisture control in 3D printing filaments.

4.1 The Critical Need for Filament Drying in 3D Printing

3D printing filaments, particularly hygroscopic varieties like Nylon, PVA, and even PETG, readily absorb moisture from the ambient environment. This moisture absorption is not merely a storage concern but significantly impacts print quality and structural integrity.

When moisture-laden filament is extruded through a hot nozzle, the water rapidly converts to steam, causing a range of defects including bubbling, stringing, poor layer adhesion, and potential nozzle clogs. Research indicates that properly dried filament can reduce misprinting by up to 20% and potentially reduce printer repair costs by up to 50%.

The industry has responded with various drying solutions, from professional-grade systems like the BigRep SHIELD, which achieves remarkable 0.01% humidity levels, to consumer products like the Creality Filament Dry Box 2.0 that operates in the 45-65°C range. DIY solutions have also proliferated, with enthusiasts creating systems ranging from modified food containers with desiccants to more sophisticated heated chambers.

4.2 Thermodynamic Principles of Dehumidification

4.2.1 Psychrometrics and Moisture Control

The scientific foundation of our filament drying system is rooted in psychrometrics-the study of air-water mixtures. A fundamental principle is that warmer air can hold significantly more moisture than cooler air. This relationship is visualized on psychrometric charts, which plot temperature against humidity and demonstrate that a 10°F rise in air temperature can decrease relative humidity by approximately 20%. Our system leverages two key thermodynamic processes:

- **Evaporation Phase:** When ambient temperature increases inside the sealed box, the moisture content capacity of the air increases, drawing moisture out from the filament material through evaporation.
- **Condensation Phase:** The moisture-laden air contacts the cold surface of the Peltier cooler, dropping below its dew point temperature, causing water vapor to condense into liquid form that can be collected and removed from the system.

4.3 PTC Heating Technology

Positive Temperature Coefficient (PTC) ceramic heaters represent an optimal choice for this application due to their self-regulating properties. Unlike conventional resistive heaters, PTC elements increase in resistance as their temperature rises, creating an inherent safety mechanism that prevents overheating. This self-regulation characteristic ensures that our system maintains optimal drying temperatures without risk of damaging temperature-sensitive filaments like PLA or TPU.

4.4 Thermoelectric Cooling Technology

The Peltier effect, discovered by Jean Charles Athanase Peltier in 1834, creates a temperature differential when electric current flows through a junction of two different materials. Modern thermoelectric coolers (TECs) utilize semiconductor materials to create cold and hot sides when voltage is applied. Compared to traditional compressor-based dehumidifiers, Peltier-based systems offer several advantages for our application:

- **Compact Size:** The solid-state nature allows for a smaller footprint
- **No Moving Parts:** Increased reliability with fewer mechanical failure points
- **Precise Temperature Control:** Direct electronic control of cooling power

- **No Refrigerants:** Environmentally friendly operation without chemical coolants

Recent studies have demonstrated that solid-state dehumidifiers can achieve humidity levels as low as 8-9% in controlled environments, outperforming traditional desiccant methods which typically plateau around 25%.

5 Major Modules Design and Implementation

5.1 Heating Module: PTC Ceramic Heater

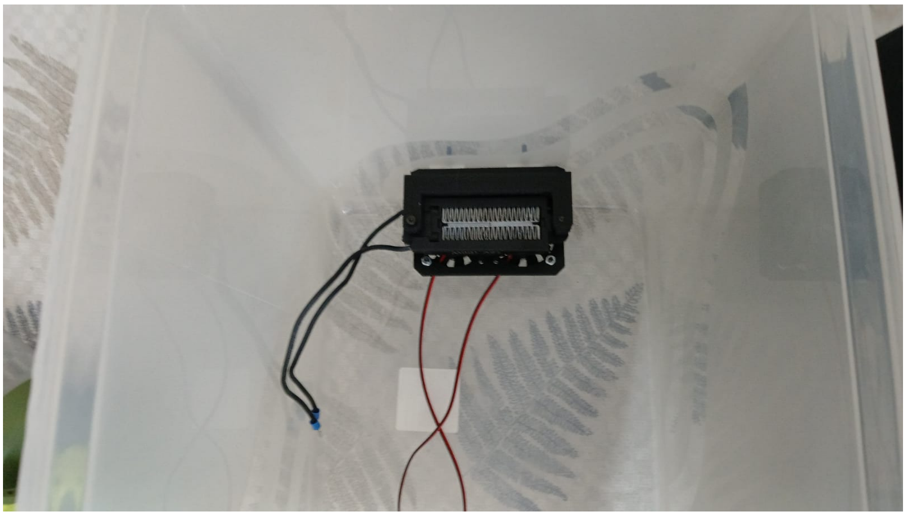

Figure 1: PTC Ceramic Heater Module

Description: This module provides the controlled heat necessary to drive moisture out of the filament material.

5.1.1 Working Principle

PTC (Positive Temperature Coefficient) ceramic heaters increase their resistance as they heat up, naturally limiting current and stabilizing temperature (typically around 60°C). The ceramic heater emits uniform heat that warms the air inside the sealed box. A 12V DC fan is paired with the heater to actively circulate warm air within the chamber, ensuring consistent drying across the entire filament spool.

5.1.2 Functionality

Self-regulating – No need for external thermal switches or thermostats. Safe and efficient – Won't overheat; energy-efficient after stabilizing. Compact & quiet – Suitable for a closed box environment.

5.2 DC Fans – Air Circulation

Description: Ensures uniform temperature distribution and prevents thermal pockets within the drying enclosure.

5.2.1 Functionality

Even airflow enhances drying efficiency by exposing all surfaces of the filament to warm air. Two or more fans may be used—one to blow heated air across the filament, another to assist air movement toward the Peltier cooler for dehumidification.

5.2.2 Key Components

- 12V brushless DC axial fans.
- Controlled via relays and optionally modulated using PWM from the ESP32.

5.3 Dehumidification Module – Peltier Cooler with Condensation Tray

Description: The Peltier module condenses moisture from the air after it has been heated and saturated with vapor from the filament.

5.3.1 Working

The TEC1-12706 Peltier module uses the thermoelectric effect: when powered, one side becomes cold, and the other becomes hot. The cold side, placed inside the box, cools humid air. As the air's temperature drops below the dew point, moisture condenses into liquid form on a metal heat sink. This condensate is collected in a tray or routed out via a tube.

5.3.2 Thermal Setup

The hot side of the Peltier is mounted on the outside of the box, with a fan and heat sink to dissipate waste heat.

5.4 Control Module – ESP32 Microcontroller System

Description: The ESP32 microcontroller handles real-time control, monitoring, and automation of all components.

5.4.1 Functionality

Reads temperature and humidity via sensors like DHT22 or SHT31. Based on sensor inputs, it:

- Activates/deactivates the heater.
- Turns fans on/off or modulates their speed via PWM.
- Controls the Peltier cooler to prevent overcooling or unnecessary power drain.

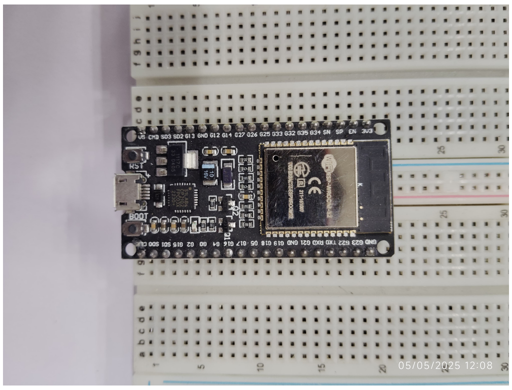

Figure 2: ESP32 Development Board

Has Wi-Fi and Bluetooth for potential IoT integration, like:

- A web dashboard.
- MQTT reporting.
- Over-the-air updates (OTA).

Interfaces: Relay module (3-channel) connected to ESP32 controls high-power elements (heater, cooler, fans). Optional OLED or LCD display for live status.

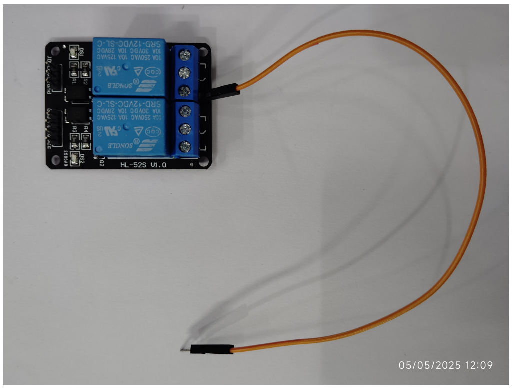

Figure 3: 12V Dual Channel Relay

5.5 Power Supply Module – 12V, 20A DC Power Unit

Figure 4: 12V 20A DC SMPS

Description: This module provides a regulated 12V supply to power the heater, fans, Peltier, and control electronics.

5.5.1 Specifications

- Voltage: 12V DC
- Current: Up to 20 Amps (sufficient for simultaneous operation of all modules)
- Features: Overcurrent, overvoltage, and thermal protection.

Figure 5: 12V 20A DC SMPS

5.5.2 Power Distribution

- Heater (100–150W) and Peltier (60–80W) draw the most current.
- Fans and ESP32 use negligible current (<1A combined).
- Proper wiring with fuses is recommended to avoid short circuits.

5.6 Enclosure – Airtight Chamber

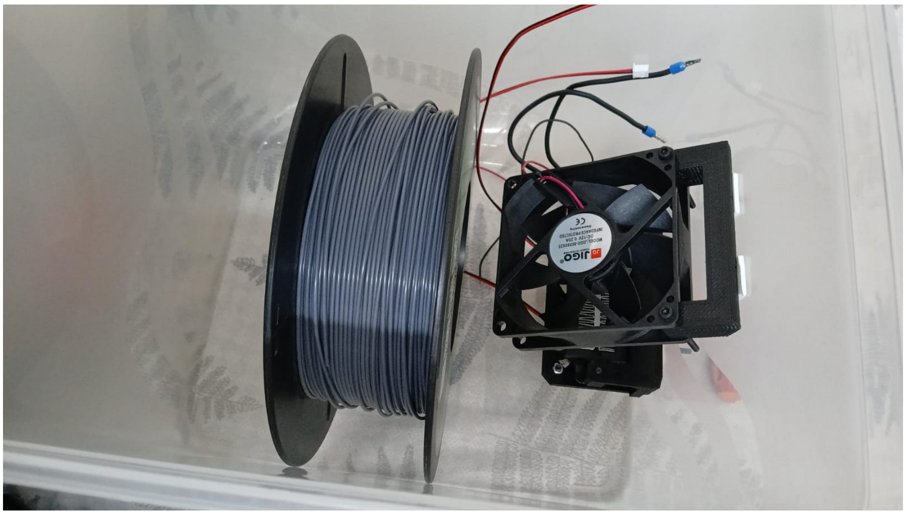

Figure 6: Enclosure

Description: The enclosure forms the physical drying environment. Its design ensures:

- Airtightness – To prevent fresh ambient humidity from entering.

- Thermal retention – To keep the internal temperature stable.
- Safety – To prevent exposure to hot components.

Includes:

- Inlet/outlet ports for filament spools.
- Access panel for cleaning and servicing.
- Drainage path for condensed water.

6 Desgin Flow

Flowcharts are visual representations of processes that illustrate the sequence of steps and decision points using standardized symbols. The flowchart in the image demonstrates a temperature control system with heating and cooling mechanisms.

6.1 Flowchart

The flowchart depicts a temperature control system that functions as follows:

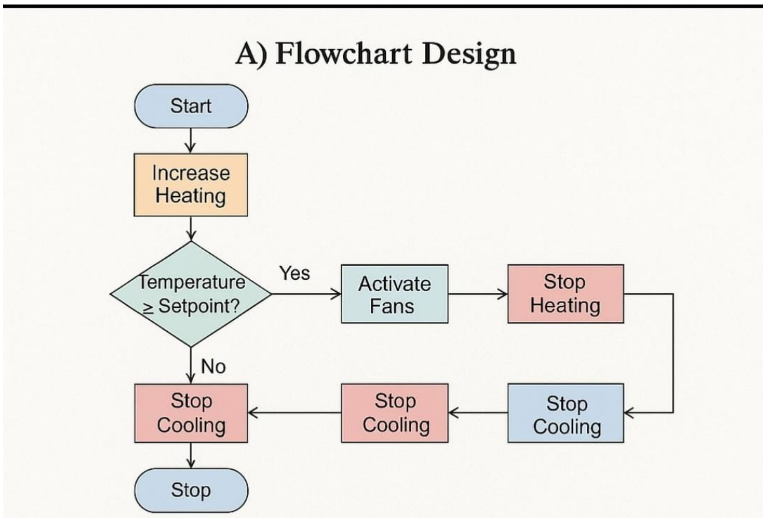

Figure 7: Flowchart

1. The process begins at "Start"
2. The system initiates by "Increase Heating"
3. At the decision point, the system checks if "Temperature $\geq$ Setpoint?"
4. If "Yes," the system will "Activate Fans" and then "Stop Heating"
5. If "No," the system will "Stop Cooling" and terminate the process
6. After "Stop Heating," the process flows to a series of "Stop Cooling" actions before potentially continuing the process.

This flowchart effectively illustrates a basic temperature regulation system, though there are some redundancies in the "Stop Cooling" actions that might benefit from refinement. Flowcharts like this are particularly valuable for visualizing control systems and processes with clear decision points.

6.2 Data Flow Diagram

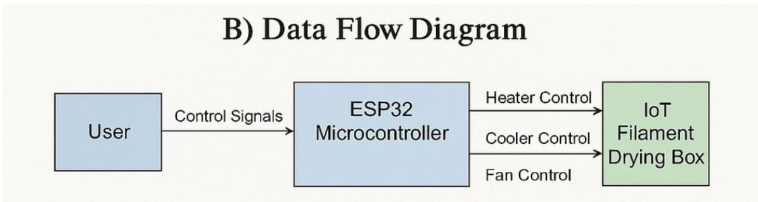

Figure 8: Data Flow Diagram

The DFD illustrates the data exchange in an IoT filament drying box system: The “User” entity sends “Control Signals” to the "ESP32 Microcontroller" process The “ESP32 Microcontroller” process transforms these signals and sends three types of control data to the “IoT Filament Drying Box” entity:

- “Heater Control” data
- “Cooler Control” data
- “Fan Control” data

6.3 Entity-Relationship Diagram

The E-R diagram depicts the relationships in an IoT filament drying box system:

- The "Filament" entity "CONTAINS" the "IoT Filament Drying Box" entity.
- The "Relay" entity "MANAGES" the "IoT Filament Drying Box" entity.
- The "MANAGES" relationship connects to "SWITCHES".

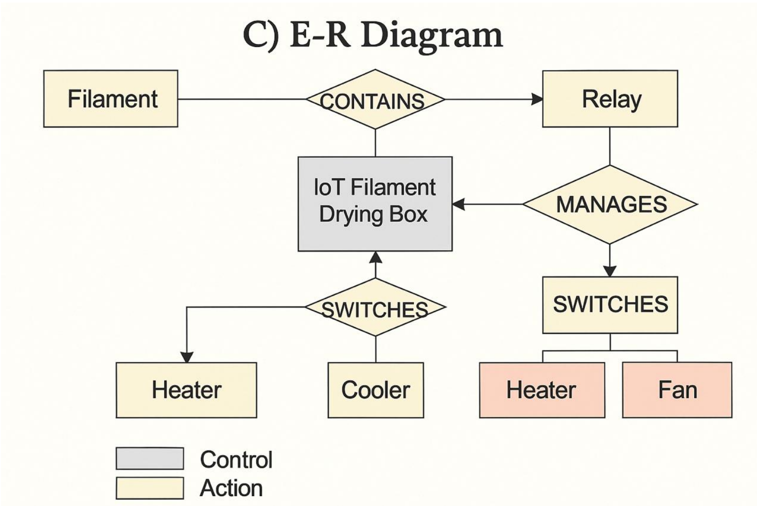

Figure 9: Entity Relationship Diagram

- The "IoT Filament Drying Box" entity "SWITCHES" both the "Heater" and "Cooler" entities.
- Additionally, "SWITCHES" connects to both "Heater" and "Fan" entities.

7 Methodology Adopted

7.1 Algorithm Formulated

7.2 Mathematical Modelling

7.2.1 Proportional Integral Derivative Controller

PID (Proportional–Integral–Derivative) controller helps maintain a set temperature or RH

General PID Equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}$$

Where,

- $e(t)$: error = setpoint - measured value
- K_p: Proportional gain
- K_i: Integral gain
- K_d: Derivative gain

7.2.2 Psychrometric Curve (Humidity vs Temperature)

Psychrometrics tells us how relative humidity (RH) decreases when temperature increases, even if the actual moisture content stays constant. We can use this curve to understand when moisture in filament will evaporate at a given temperature:

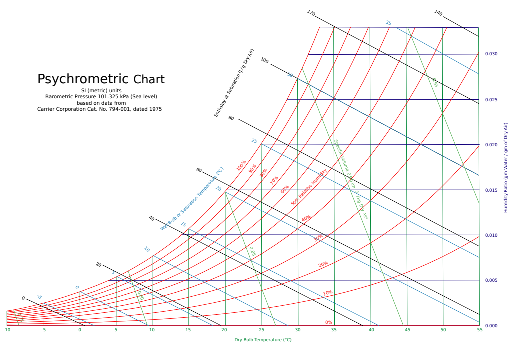

Figure 10: Psychrometric Chart

7.3 Simulation Environment

Due to the practical nature of the project, no software-based simulation tools were used. Instead, a real-time hardware prototyping environment was adopted to validate and fine-tune the system's behavior. The ESP32 microcontroller was programmed and directly interfaced with three power MOSFETs, each controlling the PTC ceramic heater, fans, and Peltier cooling module. Sensors such as DHT22 were integrated to continuously monitor internal temperature and humidity.

Testing was carried out inside a sealed acrylic enclosure designed to emulate operational conditions. System behavior was manually logged and observed under various heating durations, filament types, and ambient conditions. Control logic was iteratively refined by adjusting thresholds and delays based on actual performance data. Output from the ESP32 was monitored via serial communication for debugging, and temperature/humidity values were logged to evaluate moisture removal efficiency. This hands-on approach allowed for accurate observation of thermal response, condensation efficiency, and hardware stability, providing a realistic validation of system performance without relying on virtual simulation tools.

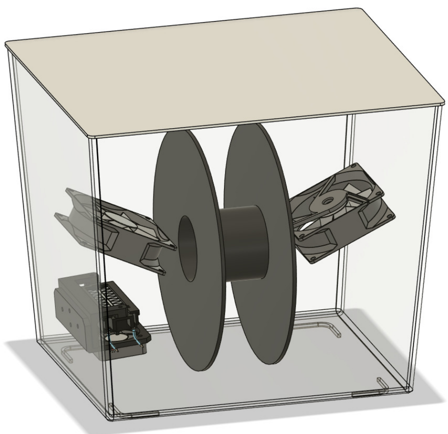

Figure 11: CAD Model

8 Results

8.1 Screen Shot of Simulator/Emulator/Hardware Kits

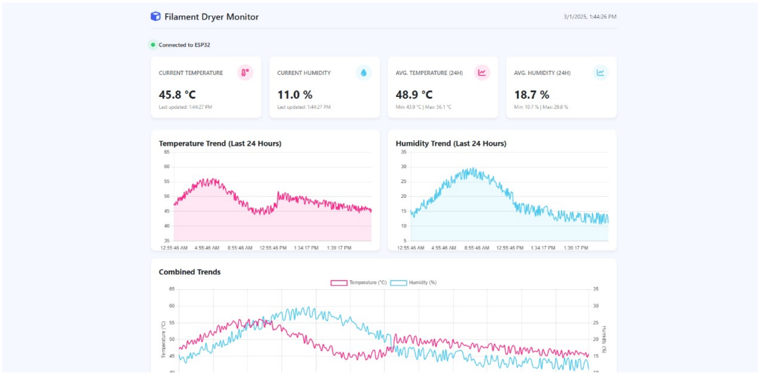

Figure 12: Web Application

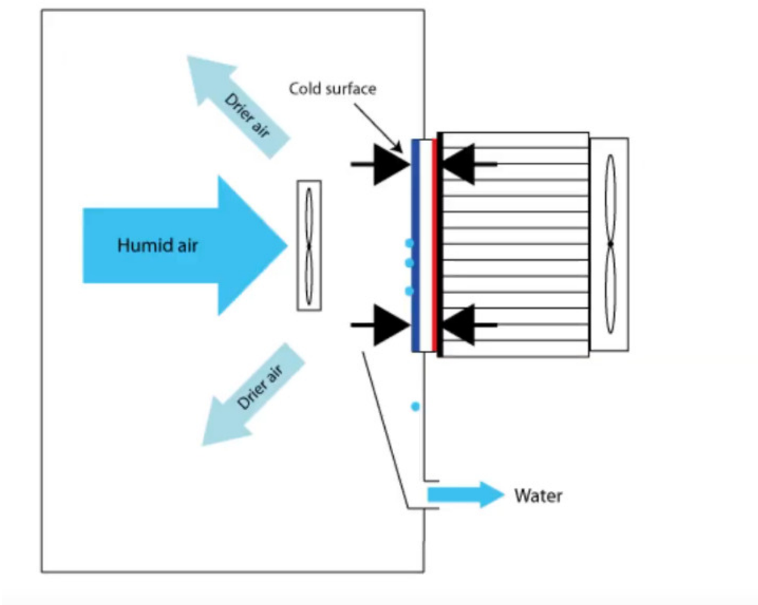

Figure 13: Condensation using Peltier Module

8.2 Graphs and Tables

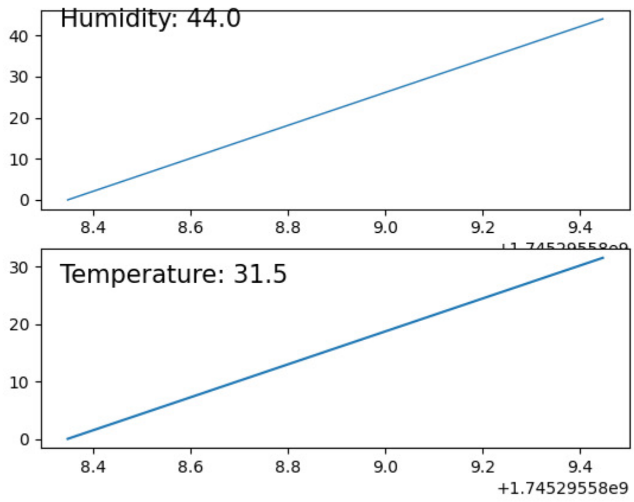

Figure 14: DHT22 Sensor Readings

8.3 Comparitive Chart

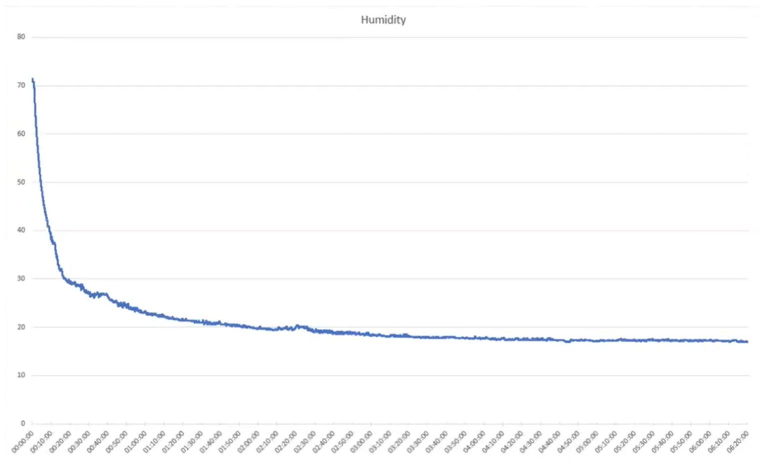

Figure 15: Humidity Graph

9 References/Bibliography

Here are the key references and sources related to filament drying systems and moisture management in 3D printing:

References

[Fee22] Workshop Feedback. *I designed an air dryer with a Peltier module to keep my coreXY printer filaments dry while printing.* Accessed: 2025-05-05. 2022. URL: https://youtu.be/mAJJ_QABxpg.

[Boi25] Tess Boissonneault. *How to Dry Filament: PA, TPU, PLA, PVA & PET.* Accessed: 2025-05-05. 2025. URL: https://www.wevolver.com/article/how-to-dry-filament.

[Con24] IVDx Consulting. *Dry Boxes for MMU3 Filament Feed.* Accessed: 2025-05-05. 2024. URL: https://www.printables.com/model/920522-dry-boxes-for-mmu3-filament-feed.

[Cre24] Creality. *Creality Space Pi Filament Dryer, Filament Storage Box, Upgraded Double 360° Heating Drying with FanTouch Screen, 3D Printer Filament Spool Holder, Dehydrator 1.75/2.85/3mm PLA PETG ABS TPU Nylon.* Accessed: 2025-05-05. 2024. URL: https://www.amazon.com/dp/B0CPJF3BSS.

[Hum23] Huminilian. *What is the 3d filament dryer you choose?* Accessed: 2025-05-05. 2023. URL: https://forum.bambulab.com/t/what-is-the-3d-filament-dryer-you-choose/17256.

[Gun24] GunplaMark. *Dry Box Storage System for 3D Printer Filament, Updated for 2024 and Better than Ever!* Accessed: 2025-05-05. 2024. URL: https://www.youtube.com/watch?v=YuO7iVL-4Cg.

Figure 16: From Left to Right: Soham Khanna, Parikshit Pandey, Sujal Singh, Pranav Bisht, Dhruv Grover