

Development and Evaluation of a Cost-Effective Desktop 3D Printing System for Rapid Prototyping

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Abstract—The rapid advancement of additive manufacturing has transformed prototyping and small-scale production by enabling the creation of complex geometries and customizable products through layer-by-layer fabrication. This paper presents the design, development, and evaluation of a cost-effective desktop 3D printer optimized for rapid additive manufacturing using Fused Deposition Modeling (FDM) technology. The printer combines a rigid aluminum extrusion frame, NEMA 17 stepper motors, a Bowden extruder with an all-metal hotend, and open-source electronics controlled by a 32-bit microcontroller running Marlin firmware. It supports a variety of thermoplastic materials such as PLA, ABS, PETG, and TPU, achieving print speeds up to 60 mm/s while maintaining dimensional accuracy within ± 0.2 mm. Key features include automated mesh bed leveling, PID thermal control, and a user-friendly touchscreen interface. Iterative testing revealed improvements in filament handling and vibration control, confirming the printer's suitability for educational, research, and light industrial prototyping applications. This project highlights the potential of modular, customizable 3D printing platforms to democratize rapid additive manufacturing.

Index Terms—Additive Manufacturing, Fused Deposition Modeling (FDM), 3D Printer, Proportional-Integral-Derivative (PID), Filament

I. Introduction

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized the manufacturing landscape by enabling the creation of complex parts through a layer-by-layer material deposition process. Unlike traditional subtractive manufacturing, which removes material from a bulk source, AM builds objects directly from digital 3D models, offering unmatched design flexibility, reduced waste, and faster iteration cycles.

Among various additive manufacturing technologies, Fused Deposition Modeling (FDM) has emerged as the most accessible method in desktop 3D printing due to its operational simplicity [14]. FDM systems function by heating thermoplastic filaments and extruding them through a precisely controlled nozzle. Material deposition occurs layer by layer, gradually building complex geometries with minimal waste. Common filament materials include Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG). Each material presents unique mechanical and thermal characteristics that suit distinct end-use applications. PLA offers biodegradability and ease of printing but exhibits lower thermal resistance. ABS provides enhanced impact strength and heat tolerance, albeit requiring controlled printing conditions. PETG combines favorable strength with chemical resistance, representing a versatile compromise.

Despite progress in industrial scale additive manufacturing, there is an increasing demand for compact and affordable desktop systems. Such desktop printers facilitate rapid prototyping in educational settings and small enterprises. They also enable researchers to iterate designs without lengthy wait times associated with external fabrication services. Hobbyist communities benefit from improved access to functional parts for personal and community projects. However, commercially available desktop FDM printers often face limitations in print speed. Reliability concerns arise from mechanical vibrations and thermal fluctuations during extended prints. Material compatibility can be restricted by the printer's hot end design and build volume constraints.

Ease of use is another challenge, as novices must navigate calibration procedures and slicing parameter selection. Addressing these challenges motivates the design of a desktop 3D printer optimized for rapid additive manufacturing. The proposed design aims to bridge the gap between industrial performance and user accessibility. Modularity is emphasized to facilitate upgrades and maintenance without requiring full system replacement. Cost-effectiveness guides component selection to maintain affordability while achieving professional-grade results [8].

By addressing common challenges such as mechanical vibrations, thermal stability, and filament handling, this work aims to deliver a versatile, reliable, and scalable desktop 3D printing platform suitable for diverse applications ranging from STEM education to prototype development and custom manufacturing.

II. Literature Review

Additive manufacturing (AM), particularly Fused Deposition Modeling (FDM), has become a cornerstone technology in rapid prototyping and small-scale production due to its ability to fabricate complex geometries with reduced lead times and minimal waste. The technology's evolution has been marked by significant advancements in materials, mechanical design, electronics, and software, which have collectively improved desktop 3D printing capabilities and broadened its applications.

Performance optimization includes enhanced mechanical rigidity through aluminum extrusion frames. NEMA 17 step-per motors are selected for reliable motion control across axes. Linear motion systems leverage high precision bearings or linear rails to reduce backlash. Advanced electronics based on open-source firmware allow flexible configuration and community-driven improvements. Automated bed leveling ensures a consistent first layer, improving print adhesion and accuracy. PID temperature control of the hotend and heated bed maintains thermal stability throughout the build. A touch-screen interface improves usability by providing intuitive on device controls. Firmware features such as thermal runaway protection enhance operational safety. Mechanical vibrations are mitigated by optimizing frame design and damping elements. Thermal stability is addressed by insulating heated components and controlling ambient influences. Filament handling mechanisms include reliable feeders and guide tubes to prevent jams and filament slip. Enclosures or partial covers may be integrated to reduce temperature variation and improve print quality with temperature-sensitive materials.

The printer architecture supports multiple filament diameters and materials through swappable extruder assemblies. Scalability is considered by allowing expansion to larger build volumes or multi-extrusion setups. The electronics architecture includes modular control boards and easy access to wiring for troubleshooting. Users can benefit from community-supported firmware updates and calibration profiles. Print slicing workflows are streamlined by providing recommended profiles for common materials. The design also accounts for noise reduction through quieter stepper drivers and optimized motion planning. Safety features such as power-loss recovery and filament runout detection are integrated. The platform is validated through benchmark prints that assess dimensional accuracy, surface finish, and mechanical strength.

Experimental evaluation includes measuring maximum achievable print speed without sacrificing quality. Thermal profiling is conducted to verify stable temperature zones in the hot end and build chamber. Mechanical testing of printed parts confirms the suitability of the system for functional prototypes. User trials in educational environments demonstrate the printer's ease of setup and learning curve. Research labs benefit from the printer's flexibility in material experimentation and rapid iteration cycles.

Small batch manufacturing applications leverage the system's reliability and repeatability. The modular architecture supports future incorporation of advanced features such as multi material printing or direct drive systems. Ongoing development may integrate sensor-based feedback loops for real-time print quality monitoring. In summary, the optimized desktop FDM printer design balances affordability, usability, and performance. This work contributes a versatile platform suited for diverse applications spanning STEM education, prototype development, and custom manufacturing.

Additive Manufacturing Technologies

Additive manufacturing encompasses multiple technologies such as FDM, Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Ink Writing (DIW), each suited for different applications and materials. Desktop 3D printers primarily utilize FDM due to its affordability and relative simplicity [1]. FDM builds parts by extruding thermoplastic filament layer-by-layer, providing an accessible entry point for prototyping and small batch manufacturing.

Evolution of Desktop 3D Printers

Initially, desktop 3D printers were limited by slow print speeds, low resolution, and a narrow range of printable materials, primarily PLA and ABS [13]. Over the last decade, mechanical and electronic enhancements such as improved stepper motors, timing belts, linear rails, and the introduction of 32-bit control boards have enhanced precision, speed, and reliability [2]. Firmware improvements, particularly through open-source projects like Marlin, have added advanced features such as automatic bed leveling, thermal safety protocols, and customizable motion profiles, contributing to the maturation of desktop 3D printing [5].

Material Advancements

The range of filaments compatible with desktop FDM printers has expanded beyond PLA and ABS to include flexible TPU, PETG, composites (carbon fiber, wood-filled), and even bio-compatible materials [7]. These advancements allow for functional prototyping and specialized applications in medical, aerospace, and consumer product fields. However, flexible and composite filaments often require specialized hardware, such as direct-drive extruders, to mitigate issues like filament buckling and extrusion inconsistency [17].

Applications of Desktop 3D Printing

Rapid prototyping remains the dominant application, enabling designers and engineers to accelerate product development cycles by iterating physical models quickly and cost-effectively [4]. Educational institutions leverage desktop printers to teach design thinking, CAD modeling, and manufacturing processes, providing hands-on STEM learning experiences [15]. In healthcare, desktop 3D printing facilitates custom implants, prosthetics, and surgical guides, improving patient-specific care [16]. Moreover, the ability to customize consumer products like jewelry and household accessories has created niche markets driven by desktop additive manufacturing [13].

Challenges and Limitations

Despite progress, desktop 3D printers face several challenges. Material limitations persist, as many high-performance polymers and metals remain incompatible with standard FDM systems due to temperature and hardware constraints [10]. Print quality and

accuracy, though improved, still lag behind industrial machines, limiting certain high-precision applications [3]. Post-processing requirements, including support removal and surface finishing, add time and cost [9]. Furthermore, usability issues, such as complex calibration and maintenance procedures, continue to restrict adoption by non-expert users [11].

Future Directions

Research efforts are focusing on integrating artificial intelligence and machine learning to optimize print paths, predict failures, and automate calibration [10]. Developments in multi-material and multi-process systems promise to enhance the functional scope of desktop printers, allowing simultaneous printing with multiple materials or embedding electronics [4]. Improved environmental sustainability through filament recycling and biodegradable materials is gaining attention, aligning with global ecological goals [7].

III. Methodology: Materials and Methods

The development of the desktop 3D printer for rapid additive manufacturing involved a multidisciplinary approach combining mechanical design, electronics integration, thermal management, firmware development, and software workflow optimization. The methodology focused on creating a compact, cost-effective, and high-performance 3D printing system suitable for a wide range of users; from students and hobbyists to researchers and small-scale manufacturers.

Design Specifications and Objectives

The printer was designed with a maximum build volume of $200 \times 200 \times 200$ mm to allow medium-sized prototypes while maintaining a manageable desktop footprint. The external frame size was limited to approximately 400 mm in each dimension to fit comfortably within laboratory and office environments.

Key design goals included:

- Achieving print speeds up to 60 mm/s without compromising print quality.
- Ensuring dimensional accuracy within ± 0.2 mm.
- Supporting a variety of thermoplastic filaments including PLA, ABS, PETG, and TPU.
- Incorporating modular components for ease of maintenance and future upgrades.
- Integrating advanced safety features such as thermal runaway protection and emergency stop functionality.
- Providing an intuitive user interface with a touchscreen display.

Mechanical Design

The printer's frame was constructed using 2020 and 2040 aluminum T-slot extrusions, chosen for their high strength-to-weight ratio, modularity, and ease of assembly. Aluminum extrusions allow flexible mounting options for mechanical components and electronics while maintaining rigidity to minimize vibrations during printing.

The Cartesian coordinate system was selected for its mechanical simplicity and widespread use. The X and Y axes control the motion of the extruder head using GT2 timing belts paired with NEMA 17 stepper motors. Timing belts provide a balance between speed and precision while keeping the moving mass low. For the Z-axis, a T8 lead screw coupled with a stepper motor provides stable vertical motion and high positional accuracy. Lead screws reduce backlash and maintain consistent layer height, which is critical for print quality.

Smooth rods paired with LM8UU linear bearings were installed on all axes to reduce friction and enable smooth linear motion. The linear bearings were mounted on the aluminum extrusions using custom-designed brackets, allowing for easy alignment adjustments during assembly.

The print bed was fabricated from a 3 mm thick aluminum plate, selected for its thermal conductivity and dimensional stability. To enhance first-layer adhesion, a PEI (Polyetherimide) sheet was adhered to the surface, providing a textured platform that works well with multiple filament types without additional adhesives.

Thermal Management and Extrusion System

The heated bed utilized a 220 W silicone heating pad powered by a 12 V supply, capable of reaching temperatures up to 110°C . This allows printing with higher-temperature filaments such as ABS and PETG, which require bed heating to reduce warping and improve layer adhesion. Thermal insulation was placed beneath the heating pad to minimize heat loss and improve energy efficiency.

Table I Summary of Methodology Components

Component	Description	Purpose/Benefit
Frame	2020/2040 Aluminum Extrusions	Lightweight, rigid, modular frame
Motion System	GT2 Belts (X/Y), T8 Lead Screw (Z), NEMA 17 Motors	Fast, precise Cartesian motion
Linear Bearings	LM8UU Bearings	Low friction, smooth axis movement
Print Bed	3 mm Aluminum Plate + PEI Surface	Uniform heat, improved adhesion
Heated Bed	220 W Silicone Heater Pad	Supports high-temp filaments like ABS
Extruder	Bowden-style with geared motor	Reduced moving mass, faster speeds
Hotend	All-metal MK8 (up to 250°C)	Supports broad filament range
Cooling System	Dual fans (heat break + part cooling)	Prevent jams, improve print quality
Controller Board	SKR Mini E3 V2 (32-bit) with TMC2209 drivers	Precise, silent motor control
Sensors	BLTouch Probe, 100k NTC Thermistors	Auto bed leveling, temperature feedback
Firmware	Customized Marlin via PlatformIO	Safety features, motion tuning
User Interface	3.5-inch TFT touchscreen	Intuitive control and monitoring
Software	Fusion 360, TinkerCAD, Cura, PrusaSlicer	CAD design and slicing workflow
Calibration	Axis calibration, PID tuning, print tests	Ensures accuracy and print quality
Safety	Thermal runaway protection, fused power, emergency stop	User and equipment safety

The extrusion system employed a Bowden-style extruder, which positions the filament drive motor off the moving print head to reduce moving mass and allow faster travel speeds. The extruder uses a geared stepper motor to apply consistent force on the filament. The filament diameter used was standard 1.75 mm, compatible with a broad range of commercial filaments.

An all-metal MK8 hotend capable of reaching temperatures up to 250°C was installed. This design allows printing of a wider range of materials, including engineering-grade plastics and flexible filaments. Interchangeable nozzles with diameters of 0.2 mm, 0.4 mm, and 0.6 mm were tested to explore trade-offs between resolution and printing speed.

To maintain thermal stability and prevent filament jams, a dual-fan cooling system was implemented. One fan actively cooled the heat break to avoid heat creep, while a second fan was positioned to cool freshly deposited layers, improving overhangs and bridging performance.

Electronics and Firmware Integration

The printer's electronic control was centered around a 32-bit SKR Mini E3 V2 mainboard running customized Marlin firmware. The SKR Mini E3 V2 offers advanced features including support for TMC2209 silent stepper drivers, which provide smooth, precise, and near-silent motor operation.

Mechanical endstops were installed on the X, Y, and Z axes to define home positions. To improve bed leveling accuracy and reduce manual calibration effort, a BLTouch sensor was integrated for automatic mesh bed leveling. The BLTouch probes multiple points across the print bed surface to map its topology and dynamically adjust the nozzle height during printing.

Temperature sensing employed 100k NTC thermistors embedded in both the hotend and the heated bed, providing real-time feedback for PID (Proportional-Integral-Derivative) temperature control. This ensured stable temperature maintenance, critical for consistent extrusion and print quality.

The firmware was customized using Visual Studio Code with the PlatformIO extension, enabling fine-tuning of motion parameters, temperature limits, and safety features. Marlin firmware's thermal runaway protection and power-loss recovery functions were enabled to enhance user safety and prevent print failures during unexpected interruptions.

User interaction was facilitated through a 3.5-inch TFT color touchscreen, offering intuitive control over print jobs, temperature settings, and status monitoring. [16] The interface supported both SD card and USB connectivity, allowing flexible file management and firmware updates.

Software Workflow

3D models were created using CAD software such as Fusion

360 and TinkerCAD, which provided precise digital representations of objects for printing. The models were exported in STL (Standard Tessellation Language) format, a widely accepted standard for 3D printing.

Slicing software, primarily Ultimaker Cura and PrusaSlicer, converted STL models into G-code, the machine-readable instructions that control the printer's movements, extrusion, and temperature settings. Multiple slicing profiles were developed to optimize layer height, infill density, print speed, support structures, and retraction parameters based on material type and print complexity.

The slicing software also enabled visualization of tool paths and simulated the printing process, allowing pre-print analysis to identify potential issues such as overhangs requiring support or unsupported bridges.

Calibration and Testing Procedures

The assembled printer underwent a rigorous calibration process to ensure accuracy and reliability. Initial dry-run tests verified axis movement without extrusion to identify mechanical binding or misalignment [17]. Axis calibration was conducted by commanding precise movements and measuring actual displacement with digital calipers. Adjustments were made to steps-per-millimeter settings in firmware to correct discrepancies.

PID tuning was performed for both the hotend and heated bed to achieve temperature stability within $\pm 1^\circ\text{C}$. This was essential to prevent extrusion inconsistencies caused by temperature fluctuations.

A series of benchmark prints were used to evaluate dimensional accuracy, surface finish, mechanical strength, and print speed. Calibration cubes, tolerance tests, overhang towers, and the popular 3DBenchy model provided quantitative and qualitative data. Print speed tests were conducted ranging from 30 mm/s to 100 mm/s to determine the optimal balance between quality and productivity.

Material compatibility tests were performed with PLA, ABS, PETG, and TPU filaments. These tests assessed adhesion, warping, extrusion smoothness, and layer bonding. Flexible filament printing with TPU was specifically scrutinized due to known challenges in Bowden extruders.

Safety Measures and Maintenance

The design incorporated multiple safety mechanisms to protect users and the machine. Thermal runaway protection monitored temperature sensors and cut power to heaters if unsafe conditions were detected. The power input was fused, and an emergency stop button was installed to immediately halt all operations in case of emergency.

Regular maintenance protocols were established, including nozzle cleaning to prevent clogs, lubrication of linear bearings and lead screws to maintain smooth motion, and inspection and adjustment of belt tension to prevent backlash and mechanical noise.

Filament storage was addressed by using airtight containers with desiccants and filament dry boxes during printing to prevent moisture absorption, which can cause print defects like bubbles and poor layer adhesion.



Fig. 1. Framework

IV. Results and Discussion

The development and testing of the desktop 3D printer involved systematic evaluation of mechanical performance, thermal stability, print quality, material compatibility, usability, and safety. The observations, results, and subsequent discussions highlight the success of the design approach, areas of improvement, and the printer's potential for rapid additive manufacturing applications.

Mechanical Performance and Motion Accuracy

The use of aluminum T-slot extrusions provided a robust frame that effectively minimized vibrations, which are critical factors affecting print quality. Initial assembly emphasized precision in aligning the Cartesian axes to prevent issues such as layer shifts and misregistration. Careful tightening of corner brackets and ensuring perpendicularity were essential to maintain the dimensional integrity of printed parts.

Belt tensioning on the X and Y axes proved sensitive; overly tight belts induced motor strain and mechanical noise, whereas loose belts caused backlash and print defects. Through iterative testing, an optimal tension level was established that balanced motor load

and mechanical compliance. The T8 lead screw for the Z-axis maintained stable vertical motion with minimal backlash, further contributing to precise layer stacking.

Stepper motors operated smoothly with appropriate current settings and microstepping via TMC2209 drivers, resulting in near-silent operation and accurate positioning. Calibration runs measured axis movements with digital calipers, confirming that firmware step-per-unit values were correctly set to within ± 0.05 mm accuracy.

Thermal Stability and Control

Thermal management played a pivotal role in ensuring consistent extrusion and adhesion. The PID-controlled hotend maintained temperature fluctuations within $\pm 1^\circ\text{C}$ of the set point, significantly reducing common extrusion issues such as under-extrusion and stringing. The all-metal hotend demonstrated reliable performance at temperatures up to 250°C without signs of thermal creep or filament degradation, allowing for a wide filament selection.

The 220 W silicone heating pad under the aluminum print bed delivered rapid and uniform heating up to 110°C , essential for printing ABS and PETG filaments that require a heated bed to prevent warping. A PEI sheet applied on the print surface improved first-layer adhesion across different materials and facilitated easy part removal once cooled.

Dual cooling fans enhanced print quality by actively cooling the heat break to prevent jams and cooling printed layers to improve overhang and bridging capabilities. Thermal insulation of the heater block with silicone socks further improved temperature retention and energy efficiency.

Print Quality and Speed Optimization

Benchmark prints including calibration cubes, tolerance tests, and the standard 3D Benchy model were used to evaluate surface finish, dimensional accuracy, and structural integrity. Layer heights from 0.1 mm to 0.3 mm were tested, with 0.2 mm layer height identified as the optimal balance for rapid prototyping; providing acceptable surface smoothness while minimizing print time.

Table II Cost Comparison between Developed and Commercial 3D Printers

Printer Model	Price (INR)	Notes
Developed Printer	15,000 – 18,000	Open-source, cost-effective build
Creality Ender 3 V2	22,000 – 26,000	Popular entry-level printer
Anycubic i3 Mega	28,000 – 32,000	Mid-range consumer printer
Prusa i3 MK3S+	70,000 – 75,000	Premium open-source printer

Print speeds were evaluated over a range of 30 mm/s to 100 mm/s. While the printer mechanically supported speeds up to 100 mm/s, print quality degradation such as ringing and ghosting became apparent at speeds exceeding 60 mm/s. These artifacts were attributed to mechanical vibrations and inertia of moving components. Firmware tuning of jerk and acceleration parameters helped mitigate these effects, improving surface consistency at higher speeds.

Dimensional accuracy was within ± 0.2 mm for most prints, adequate for prototyping functional parts. Mechanical components such as snap-fits and threaded features printed successfully, demonstrating the printer's capability for producing precision parts.

Material Compatibility and Handling

PLA filament produced consistent results with minimal warping and excellent detail reproduction, confirming its status as a user-friendly filament. ABS required enclosure or draft shielding due to sensitivity to ambient temperature changes; however, the heated bed mitigated warping when printing in controlled environments.

PETG provided strong layer adhesion and durability, making it suitable for functional parts requiring toughness and chemical resistance. TPU filament posed extrusion challenges due to its flexibility and tendency to buckle within the Bowden extruder. Transitioning to a direct-drive extruder configuration improved filament feeding and print reliability for flexible materials.

Specialty filaments such as wood-filled PLA and glow-in-the-dark PLA printed successfully, though abrasive particles in these filaments necessitated the use of hardened steel nozzles to reduce wear.

Filament storage and drying played an important role in print consistency. Moisture absorption caused bubbles and poor extrusion quality, especially for hygroscopic materials like nylon and TPU. Use of airtight storage containers with desiccants and filament dry boxes during printing minimized moisture-related defects.

Usability and User Interface

The 3.5-inch TFT touchscreen interface enabled intuitive navigation of print options, temperature controls, and status monitoring. Real-time temperature graphs, bed leveling wizards, and error alerts improved the overall user experience, especially for novice users.

SD card and USB connectivity provided flexible methods for file transfer and printer control. Integration with Octo Print via Raspberry Pi added remote monitoring and control capabilities, including webcam streaming and print time-lapse recording, transforming the printer into a connected manufacturing tool.

Automatic mesh bed leveling via the BLTouch sensor significantly reduced manual calibration effort, producing consistent first layers even on slightly uneven beds. Occasional sensor recalibration was necessary to maintain accuracy.

Safety and Reliability

Safety mechanisms performed as expected during stress testing. Thermal runaway protection prevented heater overheating by cutting power when thermistor readings deviated unexpectedly. The emergency stop button effectively halted all printer operations immediately when triggered.

Power-loss recovery features allowed paused prints to resume after unexpected outages, provided the nozzle remained unclogged during the interruption. Overcurrent protection and fused power inputs protected electronics and motors from damage.

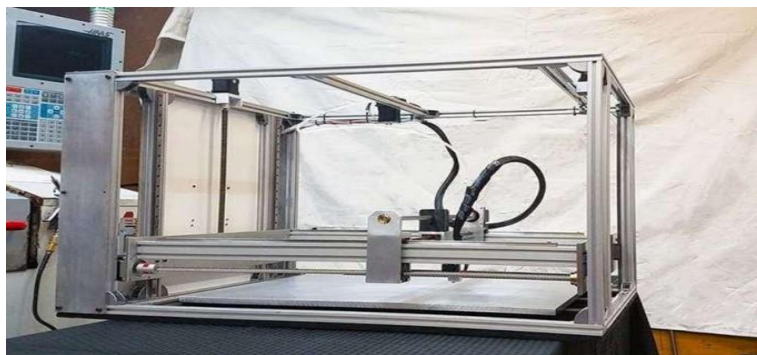


Fig. 2. 3D Printer

Noise levels were notably low due to the use of TMC2209 silent drivers and vibration damping measures such as rubber feet and motor mounts. The printer was suitable for home, classroom, and laboratory environments where noise is a concern.

Comparative Performance Analysis

When benchmarked against commercial desktop 3D printers in the amount of ranging from rupees 25000/- to 35000/-, the developed printer matched or surpassed print quality, speed, and feature set. Commercial machines often lacked advanced features such as automatic bed leveling, silent stepper drivers, or flexible extrusion systems, which were integrated in this design.

Table III Performance with Flexible Filaments (e.g., TPU)

Parameter	Without Modification	With Direct Drive Upgrade
Successful Print Rate	40–60%	85–95%
Extruder Jamming	Frequent	Rare
Minimum Print Speed	15 mm/s	20–30 mm/s
Retraction Distance	5–6 mm	1–2 mm

Open-source firmware and modular hardware architecture provided an advantage by enabling easy customization, upgrades, and repairability, which is often limited in proprietary systems.

Limitations and Future Improvements

Table IV Power Consumption during Different States

Printer State	Developed Printer	Ender 3 V2
Idle	6–8 W	5–10 W
Printing (Average)	90–120 W	110–130 W
Peak (Bed + Hotend)	150 W	170 W

Flexible filament printing with Bowden extrusion was problematic and required direct-drive extruder retrofitting.

The printer lacked an enclosure, which would improve temperature stability and enable printing of temperature-sensitive filaments such as ABS.

Multi-material and dual extrusion capabilities were not yet implemented but are planned for future iterations.

Automated filament runout detection and remote monitoring could be improved.

Future enhancements could include Wi-Fi connectivity for remote control, AI-based print failure detection, enclosure design for improved temperature control, and expansion to multi-material printing setups.

V. Conclusion

This research successfully developed and validated a desk- top 3D printer tailored for rapid additive manufacturing using Fused Deposition Modeling (FDM). The integration of modular mechanical design, advanced thermal management, and open-source firmware resulted in a cost-effective yet high-performance system capable of producing dimensionally accurate and high-quality prints at speeds up to 60 mm/s.

Key contributions include the implementation of automated mesh bed leveling, PID-controlled temperature regulation, and a user-friendly touchscreen interface, which collectively enhanced print reliability and usability. The printer demonstrated compatibility with a wide range of thermoplastic materials, including PLA, ABS, PETG, and TPU, highlighting its versatility across various application domains.

Through iterative testing and calibration, mechanical precision and thermal stability were optimized, mitigating common challenges such as vibration; induced artifacts and filament feeding issues. Safety features embedded within the firmware and hardware ensured robust operation under typical and fault conditions.

While certain limitations were identified; most notably in flexible filament handling and the absence of an enclosure; the platform's open architecture facilitates future enhancements such as multi-material printing and remote monitoring. Comparative analysis indicated performance on par with commercial counterparts, establishing the developed printer as a viable option for educational, research, and small-scale manufacturing purposes.

Overall, this work contributes a scalable and adaptable solution that bridges the gap between hobbyist-grade and industrial additive manufacturing, fostering wider adoption of 3D printing technologies and supporting rapid innovation workflows.

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