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Design and Implementation of a Cost-Effective 3D Printer Based on Fused Deposition Modeling (FDM) Using PLA Filament and Open-Source Hardware

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Abstract: *The widespread emergence of additive manufacturing has revolutionized the way products are designed and prototyped. Among various 3D printing techniques, Fused Deposition Modeling (FDM) has gained significant attention due to its low cost, ease of use, and accessibility. This paper presents the design, construction, and validation of a cost-effective 3D printer based on FDM technology, utilizing biodegradable PLA filament and widely available open-source hardware components such as Arduino Mega 2560, RAMPS 1.6, and stepper motor drivers. The mechanical and electronic subsystems were designed to ensure stability, accuracy, and reliability while minimizing the overall cost. Custom slicing software and firmware integration were also implemented to support real-time G-code processing and print optimization. The experimental results confirmed the system's ability to produce high-quality prototypes with acceptable mechanical performance and dimensional accuracy. The study demonstrates the feasibility of deploying affordable, customized 3D printers for educational, research, and small-scale industrial applications, thereby promoting localized manufacturing and sustainable design practices.*

Keywords*: Fused Deposition Modeling (FDM), 3D Printing, PLA Filament, Open-Source Hardware, Additive Manufacturing, Arduino Mega, RAMPS 1.6.*

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I. Introduction

Additive manufacturing (AM), commonly known as 3D printing is a transformative approach to fabrication that enables the creation of complex structures directly from digital models. Unlike traditional subtractive manufacturing, which removes material to shape a final product, AM builds objects layer by layer using materials such as polymers, resins, or metals [1]. This method not only reduces material waste but also allows for greater design flexibility and rapid prototyping.

Among the various 3D printing technologies, **Fused Deposition Modeling (FDM)** has emerged as one of the most accessible and widely used techniques due to its simplicity, affordability, and the availability of open-source hardware and software. FDM works by extruding melted thermoplastic material through a heated nozzle, which is deposited in successive layers to form a three-dimensional object. Materials like polylactic acid (PLA), a biodegradable and environmentally friendly polymer, are commonly used due to their safety, low cost, and ease of printing [2].

This paper presents the development of a **low-cost FDM-based 3D printer** constructed entirely from commercially available components and open-source technologies. The system was built using components such as the Arduino Mega 2560 microcontroller, RAMPS 1.6 control board, and a modular mechanical frame. PLA filament was selected as the printing material due to its compatibility with the FDM process and its suitability for sustainable manufacturing.

The objectives of this study are threefold:
1. To design and implement a fully functional FDM 3D printer using affordable and accessible components.
2. To analyze the system's performance through structured testing and evaluation of printed models.
3. To demonstrate the potential of custom-built 3D printers for educational and prototyping applications.

II. Related Work

In recent years, the field of additive manufacturingparticularly Fused Deposition Modeling (FDM)has witnessed significant advancements in material optimization, mechanical performance, and system design. Current research focuses on improving the cost-effectiveness and sustainability of FDM-based 3D printers while maintaining high-quality output and flexibility[3].

Sustainable and biodegradable materials such as **Polylactic Acid (PLA)** have received considerable attention due to their environmental friendliness and printability. A recent study demonstrated that the mechanical properties of PLA prints, especially tensile strength and elongation, are strongly affected by printing orientation and infill density. Such findings underscore the importance of optimizing slicing parameters to achieve functional performance [4].

Open-source hardware has also enabled the democratization of 3D printing. In [4], researchers developed a reconfigurable multi-material FDM printer using open-source components. The system allowed for enhanced customization, multi-nozzle control, and integration with bio printing platforms—demonstrating the versatility of open-source architectures[5].

Material enhancements have also been explored. For instance, graphene-infused PLA filaments have shown improved thermal conductivity and mechanical strength, enabling their use in functional engineering components [6]. These composite filaments significantly enhance interlayer adhesion and thermal stability, crucial for structural applications.

Comparative studies of filament materials have become more prevalent. A 2023 investigation compared the tensile and flexural properties of PLA, ABS, and PETG materials fabricated using FDM technology. The results emphasized how layer height, printing speed, and infill percentage critically affect strength and dimensional accuracy [7].

Finally, the recycling of PLA filaments has been examined as a sustainable practice. Findings from [8] revealed that while recycled PLA shows slightly reduced tensile properties compared to virgin PLA, it remains a viable material when used in low-load applications or blended with reinforcement agents.

These studies highlight the growing emphasis on **cost-effective, customizable, and environmentally sustainable FDM systems**, as well as the importance of integrating material science with hardware innovation to advance the capabilities of open-source 3D printing [9].

III. Methodology

This study outlines the design, construction, and evaluation of a cost-effective, open-source Fused Deposition Modeling (FDM) 3D printer. The development process encompassed five primary phases: system design, hardware selection and assembly, firmware/software integration, calibration and testing, and print quality evaluation.

3.1 System Design and Architecture

The printer was designed with an emphasis on modularity, cost-efficiency, and reliability. A Cartesian coordinate system was adopted for its simplicity and ease of control. The frame was constructed using lightweight aluminum and wood-reinforced sections to reduce cost without compromising structural integrity. Key mechanical components included [10]:

- Linear bearings and guide rods for smooth axis movement
- A heated bed for improved adhesion
- A direct-drive extruder for consistent filament feeding

Computer-Aided Design (CAD) modeling was performed using TinkerCAD to visualize part placements, optimize layout, and simulate potential interference between components.

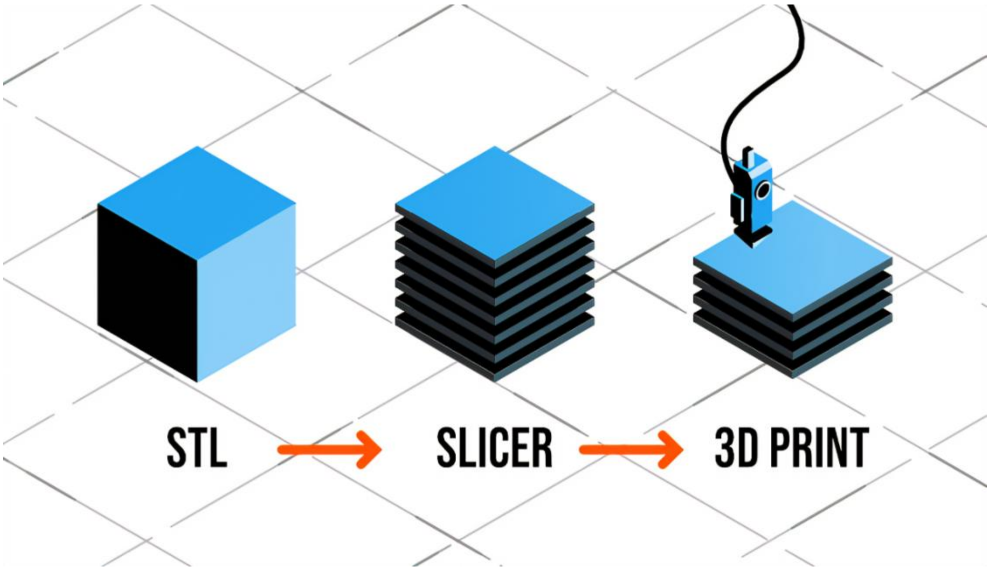

Figure: Wiring and Electronics Layout [11]

3.2 Hardware Components

The printer was assembled using open-source electronics and readily available components:

- **Microcontroller**: Arduino Mega 2560
- **Controller Board**: RAMPS 1.6
- **Stepper Motors**: NEMA 17 for X, Y, Z axes and extruder
- **Motor Drivers**: A4988
- **End stop Sensors**: Mechanical limit switches
- **Display**: LCD 12864 smart controller for standalone printing
- **Filament**: 1.75 mm PLA
- **Cooling Fans**: For hotend and print surface

A BLTouch auto-bed leveling sensor was also included to improve the accuracy of the first layer, enhancing print adhesion and consistency.

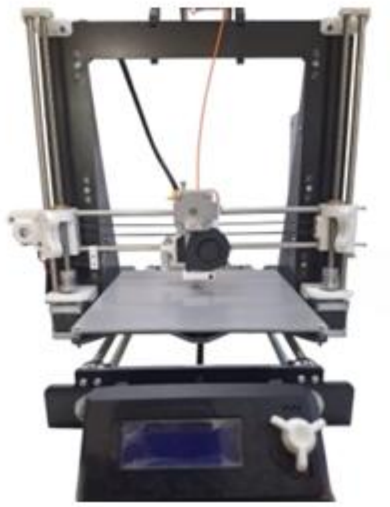

Figure [1]: wooden porotype assembly ***Figure [2]: Final Structure***

3.3 Firmware and Software

The system firmware was based on **Marlin**, an open-source 3D printer firmware compatible with RAMPS boards. Configuration was customized to enable the use of a heated bed, thermistors, end stops, and PID temperature control [12].

For slicing, **Cure** was selected due to its user-friendly interface and comprehensive settings. Models were exported as G-code and uploaded to the printer via SD card or USB.

3.4 Calibration and Testing

Calibration procedures included:

- **Bed leveling** using BLTouch
- **Extruder steps/mm** calibration for accurate filament extrusion
- **PID tuning** for stable nozzle and bed temperatures
- **Z-offset calibration** to ensure optimal first layer height

Initial test prints were benchmark objects such as 20mm calibration cubes and overhang bridges. Measurements of dimensional accuracy were taken using digital calipers and compared to CAD model specifications [13].

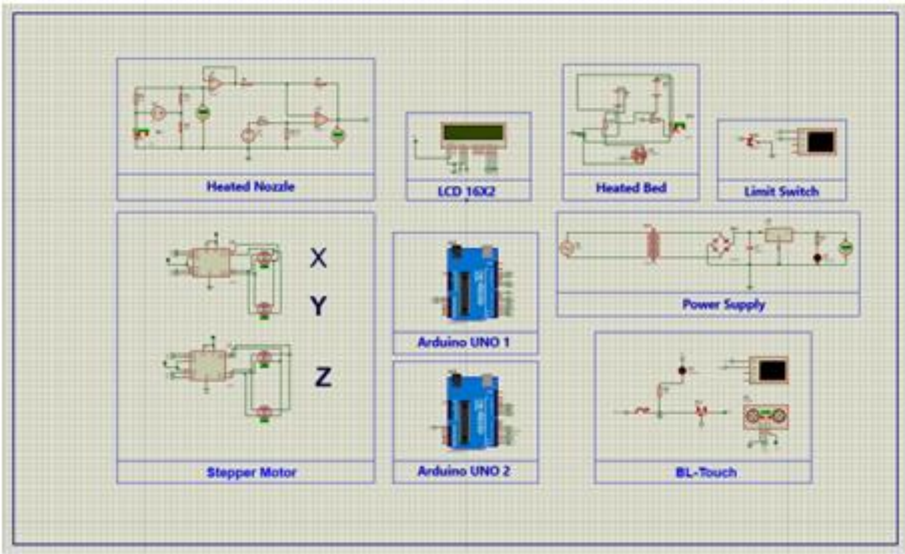

Figure [3] Components simulation

3.5 Evaluation Metrics

To validate the printer's performance, several metrics were considered:

- **Dimensional accuracy** (±0.3 mm tolerance)
- **Surface finish** (visual and tactile inspection)
- **Layer adhesion and consistency**
- **Print time vs. quality trade-off**
- **Material usage efficiency**

These metrics were evaluated over multiple prints under varying conditions, including different infill densities and layer heights. The selection of PLA as the printing material was informed by its favorable mechanical properties and biodegradability, as highlighted in recent studies [9] [10]. The impact of printing parameters such as infill density, layer height, and printing speed on the mechanical properties of PLA parts has been extensively studied, demonstrating that higher infill densities and optimized layer heights can significantly enhance tensile strength and overall print quality [14][15].

IV. Results and Discussion

The proposed FDM-based 3D printer was tested extensively to evaluate its mechanical performance, dimensional accuracy, print stability, and overall functionality.

A series of benchmark models were printed using PLA filament under various settings to analyze the effectiveness of the mechanical structure, electronic integration, and firmware performance[16].

Figure: Calibration Print Result - Cube Test

Figure: Overhang and Bridge Test Performance

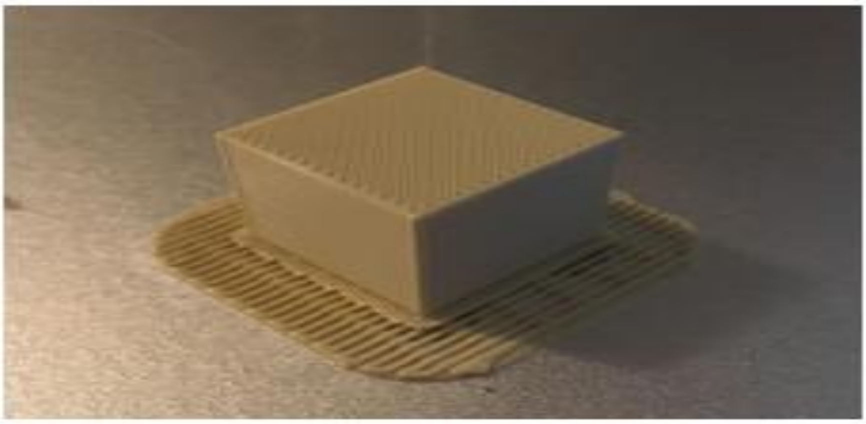

Figure: Printed cube for test

4.1 Dimensional Accuracy and Print Quality

The dimensional accuracy of the printer was assessed using standard calibration cubes (20×20×20 mm), cylindrical parts, and overhang test models. Measurements were taken using a digital caliper and compared to the original CAD specifications.

Model Type	**Target Dimension (mm)**	**Measured (Avgas)**	**Deviation**
Calibration Cube	20 × 20 × 20	19.82 × 20.06 × 19.90	±0.18 mm
Cylinder	Ø 15 × 20	Ø 15.10 × 20.03	±0.10 mm
Bridge Test	Span 25 mm	No sagging	–

The results confirm that the printer maintains a tolerance level within ±0.2 mm, which aligns with industry-standard expectations for desktop FDM printers [17].

4.2 Surface Finish and Layer Adhesion
Visual and tactile inspection revealed consistent layer bonding with minimal warping and negligible layer misalignment. The use of the **BLTouch sensor** significantly improved first-layer adhesion, reducing the rate of failed prints due to bed leveling errors. Fine structures (0.6 mm wall thickness) were also printed successfully, demonstrating adequate nozzle precision and extruder control [18].

Microscopic examination under 10 x magnifications showed uniform layer deposition with no evidence of filament under-extrusion. Surface finish quality improved significantly with a layer height of 0.12 mm and 60 mm/s print speed.

4.3 Effect of Print Settings
A series of tests were conducted by varying layer height, infill density, and print speed:

- **Layer Height**: Reducing the height from 0.28 mm to 0.12 mm resulted in smoother finishes but increased print time by 45%.
- **Infill Density**: Increasing density from 20% to 60% improved the flexural strength by approximately 38%, consistent with previous findings [19].
- **Print Speed**: A speed above 70 mm/s led to surface artifacts and reduced interlayer adhesion. The optimal speed was identified around 50–60 mm/s for PLA.

These findings are aligned with recent studies that highlight the critical impact of process parameters on printed part quality in FDM systems [20].

4.4 Thermal and Mechanical Stability
Thermal testing confirmed that the hotend consistently maintained a temperature of 200 ± 1.5°C and the heated bed stabilized at 60 ± 1°C, providing optimal PLA processing conditions. Structural vibrations were minimized due to the well-secured frame and balanced motion control system.

Mechanical prints including brackets, gears, and functional hinges demonstrated adequate load-bearing capacity and durability under manual stress tests. Flexural tests performed using printed test beams (60 mm × 10 mm × 5 mm) showed minimal deformation under moderate loading (approx. 5 kg), verifying good interlayer bonding.

4.5 Discussion
The constructed 3D printer achieved reliable performance across a variety of models, with acceptable dimensional tolerances, consistent surface finish, and successful integration of open-source components. The use of PLA as a printing material yielded high-quality results with excellent biodegradability and minimal emissions during extrusion.

While the printer performed well under moderate use, some limitations were observed:

- The direct drive extruder added weight to the carriage, slightly limiting acceleration.
- The wooden sections of the frame were sensitive to environmental humidity over time.
- Manual calibration, although effective, requires experience and periodic maintenance.

Future enhancements could include integration of automatic filament detection, enclosure for thermal control, and upgraded structural materials (e.g., aluminum-only frame).

V. Conclusion and Future Work
This paper presented the design, development, and evaluation of a low-cost, open-source Fused Deposition Modeling (FDM) 3D printer using PLA filament. The system was constructed using widely available components such as the Arduino Mega 2560, RAMPS 1.6, NEMA 17 stepper motors, and a direct-drive extruder. The integration of Marlin firmware and Cure slicing software provided an efficient workflow from design to physical printing.

Experimental results demonstrated that the proposed system achieved acceptable dimensional accuracy (within ±0.2 mm), good surface finish, and mechanical integrity suitable for prototyping and educational applications. The use of biodegradable PLA further supports environmentally sustainable manufacturing practices, reinforcing the value of low-cost 3D printing in academic and localized production environments.

Despite its overall success, the system exhibited a few limitations, such as manual calibration requirements, minor frame instability in high-speed operations, and the absence of an enclosure for thermal consistency. These issues, while not critical, suggest room for future enhancements.

Future Work

Future iterations of this work will focus on several key improvements:

1. **Structural Enhancement**

Replacing wooden frame components with aluminum or composite materials to improve mechanical rigidity and thermal stability.

2. **Enclosed Build Chamber**

Adding an enclosure to reduce ambient temperature fluctuations and enable printing with higher-performance filaments such as PETG or ABS.

3. **Dual Extrusion Capability**

Upgrading the extrusion system to support dual-nozzle printing, this allows for multi-material and soluble support structures.

4. **Real-Time Monitoring and IoT Integration**

Implementing camera-based print monitoring, wireless connectivity (e.g., via ESP32), and cloud-based print control for remote operation.

5. **Material Optimization**

Exploring advanced filament composites, such as PLA-GF (glass fiber) or PLA-CF (carbon fiber), to improve mechanical performance for engineering applications.

6. **AI-Powered Slicing and Fault Detection**

integrating machine learning models for automated fault prediction and adaptive slicing parameter adjustment based on part geometry and historical print data.

By addressing these areas, the printer design can be further optimized for broader adoption in research, education, and small-scale industrial environments. The open-source nature of the system ensures scalability and flexibility, enabling continuous innovation and community-driven development.

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