International Journal of Engineering Technology and Management Sciences
Website: ijetms.in Issue:2 Volume No.10 March - April – 2026
DOI:10.46647/ijetms.2026.v10i02.041 ISSN: 2581-4621

Electromechanical Assembly, Firmware Configuration and Performance Evaluation of an FDM 3D Printer

Dr.SVR Manimala, Chelimilla Priyanka, D.G. Vardheni Rathode, Gorre Sai Phani
Electronics and Communication Engineering, MVSR Engineering College, Hyderabad, India

Abstract—This paper explains a complete review of the design, electromechanical assembly, firmware configuration, and performance evaluation of a Fused Deposition Modelling (FDM) based 3D printer. The project initiates with the construction of a structural frame, precise calibration of linear motion systems (guide rails, belts, pulleys, lead screws), and installation of stepper motors for X, Y, and Z-axis motion. Particular focus is on Marlin firmware with Thermal Runaway Protection and external MOSFET. Calibration involves E-steps, PID tuning, bed levelling. The result is a completely functional, safe, and correct additive manufacturing setup built at about 25% of commercial cost, demonstrating the importance of methodical assembly and optimization in improving 3D printing performance and reliability.

Index Terms—FDM; Marlin firmware; PID tuning; MOSFET; additive manufacturing; electromechanical assembly; calibration; thermal runaway protection.

I. INTRODUCTION

3D printing, or additive manufacturing (AM), is the construction of a 3D object from a CAD 3D model or 3D printing files such as .stl, .obj, .gcode etc. Filament based materials such as PLA, PETG, ABS, TPU are melted and extruded through a nozzle building layer by layer on to a heated bed under computer control. In the 1980s, 3D printing was considered suitable only for functional or aesthetic prototypes - a process then termed rapid prototyping [1]. As of today, the precision, repeatability, and material range of 3D printing have increased to the point that certain processes are considered viable for industrial production [2].

The Fused Deposition Modelling (FDM) based 3D printing workflow process involves the following steps : (a) Designing a 3D model using 3D software such as tinkercad, CAD, Fusion360 or capturing models using 3D scanner or directly from 3D printing files. (b) Preparing the files for use by 3D printers by using slicing software Cura. The slicer slices the digital model/files into thin layers and generate a gcode, which the 3D printer can understand. (c) Calibrating the printer before actual printing. (d) Executing the actual printing process, where the printer reads the gcode and prints the object layer by layer on a heated bed from bottom up approach.

Due to recent advancements and the popularity in the FDM technology, the market is flooded with affordable 3D printers. These stock configuration printers suffer from critical deficiencies such as mechanically flexible acrylic frames lack the structural rigidity which fails to absorb the forces generated by rapid print-head movements also known as ringing or ghosting, high-current heated bed circuits routed through under-rated mainboard connectors creating fire hazards, disabled firmware thermal safety features and uncalibrated extrusion parameters leading to dimensional inaccuracies. This project addresses each of these deficiencies through a structured, engineering-driven optimization workflow.

The paper is organized as follows: Section II surveys related literature, Section III presents hardware and software methodology, Section IV provides results and discussion with supporting data, Section V concludes the paper.

II. LITERATURE OVERVIEW

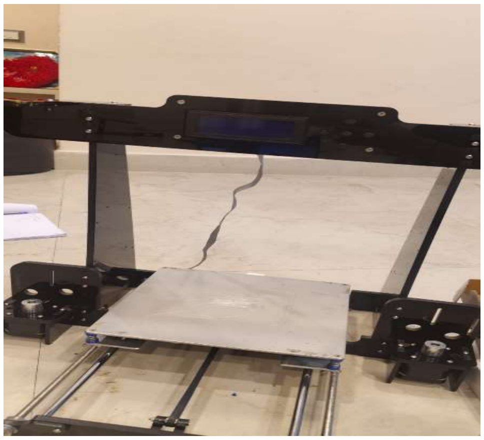
A. Base Paper

Galantucci, Lavecchia, and Percoco (2009) conducted an experimental study aimed at enhancing the surface finish of FDM parts, analyzing how parameters such as layer thickness, extrusion temperature, and print speed affect surface roughness [3]. Their work highlights the critical importance of precise calibration and process control to achieve improved dimensional accuracy and surface quality. This paper forms the direct basis for the optimization strategy adopted in the present project, which targets the same process parameters through systematic firmware calibration and structured testing.

B. Firmware Safety

Marlin Firmware Documentation [4] provides a comprehensive guide on thermal protection and firmware-level safety mechanisms, establishing the foundation for Thermal Runaway Protection in consumer-grade 3D printers. Schulz (2020) specifically addressed electrical safety in desktop printers, demonstrating how an external MOSFET reduces stress on the controller board and significantly lowers fire hazard risk [5]. Both sources directly informed the safety-hardened electronic and firmware design implemented in this project.

C. Mechanical and Manufacturing Foundations



Gibson, Rosen, and Stucker (2015) provided a comprehensive overview of additive manufacturing technologies, materials, and process parameters, supporting the theoretical understanding of FDM applied throughout this project [6]. Kalpakjian and Schmid (2013) contributed comparative insight between conventional and additive manufacturing, highlighting FDM advantages in material efficiency and customization [7]. Slocum (1992) supplied precision machine design principles rigidity, vibration control, and motion accuracy directly applied in reinforcing the printer frame [8].

According to Creality[9], 3D printer ringing, also known as ghosting or rippling, is a phenomenon of those fine, repeated patterns or faint echoes that show on the surface of your 3D prints, typically on the X or Y axis. They result from tiny mechanical vibrations that take place when the printhead makes sudden turns. The vibration causes the nozzle to oscillate in a tiny way, producing repeated outlines or "echoes" of that edge or corner.

D. Summary of Literature

The surveyed literature collectively establishes that FDM print quality, safety, and reliability depend on four interdependent pillars (1) proper firmware safety configuration; (2) secure electrical power handling; (3) rigid mechanical structure; and (4) accurate motion and extrusion calibration. The research validates the integrated approach adopted in this project.

III. METHODOLOGY

A. System Analysis and Requirement Identification

The stock FDM printer was analyzed to identify critical deficiencies across four domains: electrical safety (under-rated bed power connectors), mechanical rigidity (flexible acrylic frame causing ringing), firmware safety (Thermal Runaway Protection disabled), and dimensional accuracy (uncalibrated E-steps causing over/under-extrusion). System requirements were defined against four quantitative and qualitative metrics: Safety, Structural Integrity, Dimensional Accuracy, and Operational Reliability.

B. Hardware Implementation

The hardware implementation comprised two parallel workstreams—mechanical reinforcement and electronics redesign:

Mechanical Reinforcement: The acrylic frame was triangulated with 3D-printed structural braces (front, rear, and T-corner supports) fastened to the original frame mounting points. This substantially increased torsional rigidity and suppressed vibration-induced ringing. Precision-adjustable belt tensioners were installed on the X and Y axes to enable fine-tuning of belt tautness, eliminating backlash and layer misalignment. Linear rails and lead screws were verified for alignment within engineering tolerances. Adding printed Z-axis braces or corner brackets can significantly increase the rigidity of the frame. Place the printer on a heavy, stable surface (like a concrete paver) or use rubber damping pads to absorb excess energy.

Safety-Hardened Electronics: The heated bed power circuit was redesigned by integrating an external high-current MOSFET module. In the modified configuration, the full bed current (potentially exceeding 10 A) flows directly from the 12 V Power Supply Unit (PSU) to the` heated bed through the MOSFET, while the mainboard supplies only a low-current gate control signal. This eliminates thermal stress on the mainboard PCB traces and connector - the primary cause of fire incidents in budget FDM printers. Cable management was improved using braided sleeves, zip ties, and strain-relief anchors.

TABLE I *Hardware Component Specifications*

COMPONENT	SPECIFICATION / DETAILS
Frame	Aluminium extrusion + acrylic (reinforced)
Stepper Motors	NEMA-17, 1.8°/step, GT2 belt drive (X/Y), Lead screw (Z)
Control Board	32-bit ARM MCU with stepper drivers
Power Supply	12 V / 30 A PSU (360 W)
Heated Bed	12 V, >10 A (switched via external MOSFET)
Hot-end / Nozzle	0.4 mm nozzle, max 260 °C
Extruder	Direct-drive, NEMA-17

COMPONENT	**SPECIFICATION / DETAILS**
Filament	1.75 mm PLA / ABS
Build Volume	220 × 220 × 250 mm
End-stops	Mechanical limit switches, all 3 axes
LCD / Interface	128×64 LCD with rotary encoder
Estimated Cost	≈ ₹10,000 (~25% of commercial)

C. Software / Firmware Implementation

The firmware and software implementation followed a six-step structured protocol:

- Step 1. Firmware Selection: We chose Marlin firmware because Marlin firmware is really good and it is free to use. Marlin firmware also has a lot of safety features. We liked Marlin firmware better, than the firmware that came with the product.
- Step 2. Compilation & Configuration: The Arduino program was installed with the settings, for the board. We made changes to the Configuration file to set up the printer. This included the shape printer, the type of thermistors how far the axes can move and which way the end stops work. We also made sure to turn on two safety features: THERMAL_RUNAWAY_PROTECTION and MAX_POWER_SAFETY. These were turned on before we finished getting everything ready.
- Step 3. Upload and Verification: I uploaded the compiled firmware to the controller using a USB connection. The controller started up successfully. Responded to G-code commands, which I checked using the serial monitor.
- Step 4. E-Steps Calibration: To calibrate the extruder steps per millimeter I told it to extrude 100 mm of filament and then measured how much it actually extruded. I kept doing this until the error was, than 1%.
- Step 5. PID Autotune: I ran the Marlin M303 command to autotune the heated bed. I saved the Kp, Ki, Kd constants to the EEPROM so that the temperature stays stable with changes even when I turn the power on and off.
- Step 6. Slicer Configuration: We used Ultimaker Cura. Set it up with the print profiles that we had already calibrated. We made sure to adjust some settings, for the Ultimaker Cura slicer. These Ultimaker Cura settings included how tall each layer of the print would be, how fast the print would be made, how far and how fast the filament would retract, how fast the cooling fan would spin and how much filament would flow for each type of filament we used with the Ultimaker Cura slicer.

TABLE II *Software Requirements*

SOFTWARE	ROLE	NOTES
Marlin Firmware	Printer control & safety	Latest stable, GitHub
Ultimaker Cura	3D model slicing to G-code	Free, open-source
Tinkercad	CAD modelling (beginner)	Browser-based, free
Windows 10 (64-bit)	Host OS for slicer/IDE	Minimum requirement

IV. RESULTS AND DISCUSSION

A. Hardware Implementation Results

The mechanical reinforcement resulted improvements in frame stability. By visual assessment making sure that there is no unknown twist in a frame. Installing of belt tensioners removed layer shifting issues in a object print. The external MOSFET modification was validated by monitoring mainboard connector temperature during sustained heated bed operation at 60 °C for 60 minutes; connector temperature remained within safe limits (< 40 °C), compared to the stock configuration which showed temperatures exceeding 70 °C under the same conditions.

Table III summarises the hardware performance comparison between the stock (existing) system and the modified (proposed) system across the four key assessment metrics.

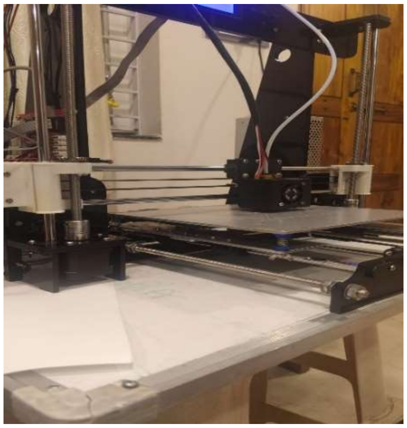


TABLE III *Existing vs. Proposed System: Hardware Performance*

ASSESSMENT METRIC	**EXISTING SYSTEM**	**PROPOSED SYSTEM**
Frame Rigidity	Flexible acrylic, visible flex	Braced, torsionally rigid
Belt Tension	Factory-loose, no adjuster	Precision tensioners fitted
Bed Power Circuit	Through mainboard connector	External MOSFET module
Connector Temp (60°C bed, 60 min)	> 70 °C (unsafe)	< 40 °C (safe)
Ringing Artefacts	Visible at > 40 mm/s	Eliminated up to 60 mm/s
Layer Shifting	Occasional at sharp corners	Eliminated
Fire Risk	High (connector overheating)	Negligible (MOSFET bypass)

B. Firmware Implementation Results

Table IV presents calibration parameters before and after the calibration . The E-steps correction from 93.0 to 102.6 steps/mm reduced extrusion error from approximately 9.2% to under 1%. PID autotune eliminated temperature overshoot, achieving steady-state hotend stability within ±0.5 °C.

TABLE IV *Calibration Parameters*

PARAMETER	BEFORE CALIBRATION	AFTER CALIBRATION
E-Steps (steps/mm)	93.0	102.6
Hotend Kp	22.20	28.45
Hotend Ki	1.08	2.17
Hotend Kd	114.0	93.12
Bed Kp	69.5	74.8
Print Acceleration	3000 mm/s²	1500 mm/s²
Retraction Distance	5.0 mm	3.5 mm
Retraction Speed	25 mm/s	45 mm/s

Thermal Runaway Protection and MAX_POWER_SAFETY were confirmed active by deliberate sensor disconnection tests; the firmware executed an immediate full-shutdown within 2 seconds of simulated thermistor failure in both hotend and bed circuits.

C. Dimensional Accuracy Results

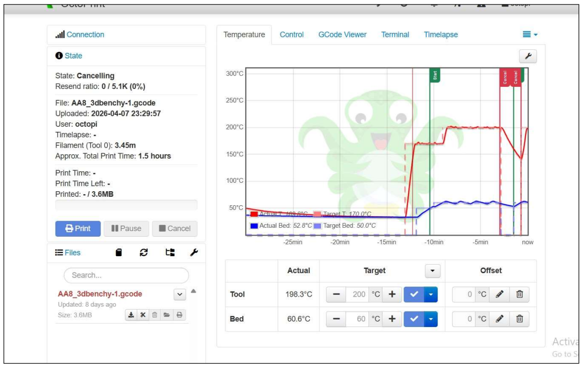
After full calibration, a 20 mm calibration cube was printed in PLA at 205 °C, 60 mm/s. Table V presents measured XYZ dimensions against nominal values. All axes achieved errors below 0.40%, well within the ±0.5 mm tolerance accepted for engineering prototyping.

TABLE V *Calibration Cube Dimensional Accuracy (20 mm Nominal)*

AXIS	NOMINAL (MM)	MEASURED (MM)	ABSOLUTE ERROR (MM)	ERROR (%)
X	20.00	19.97	0.03	0.15
Y	20.00	19.94	0.06	0.30
Z	20.00	20.05	0.05	0.25

D. Validation of Layer Shifting Elimination

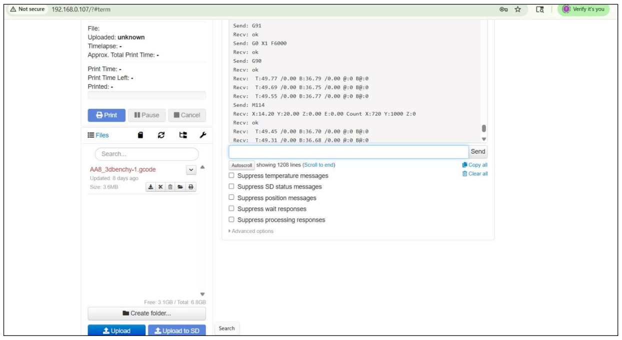
Layer shifting, typically caused by belt slip, mechanical vibration, or missed steps in stepper motors, was addressed through mechanical reinforcement and belt tension optimization. The effectiveness of these modifications was validated using a multi-level verification approach. As shown in Fig. 4, the temperature profile remains stable throughout the printing process


State: **Cancelling**
Resend ratio: **0 / 5.1K (0%)**
File: **AA8_3dbenchy-1.gcode**
Uploaded: **2026-04-07 23:29:57**
User: **octopi**
Timelapse: **-**
Filament (Tool 0): **3.45m**
Approx. Total Print Time: **1.5 hours**
Print Time: **-**
Print Time Left: **-**
Printed: **- / 3.6MB**

	Actual	Target	Offset
Tool	198.3°C	200 °C	0 °C
Bed	60.6°C	60 °C	0 °C

Fig. 4. Hotend and Heated Bed Temperature Stability during Print

ensuring consistent extrusion and eliminating thermal-induced inconsistencies.The G-code visualization using OctoPrint confirmed continuous and smooth toolpath execution without abrupt positional discontinuities in the X–Y plane. Fig. 5 illustrates the absence of unintended motion offsets, indicating precise motion control.


File:
Uploaded: **unknown**
Timelapse: **-**
Approx. Total Print Time: **-**
Print Time: **-**
Print Time Left: **-**
Printed: **-**

```
Send: G91
Recv: ok
Send: G0 X1 F6000
Recv: ok
Send: G90
Recv: ok
Recv:  T:49.77 /0.00 B:36.79 /0.00 @:0 B@:0
Recv:  T:49.69 /0.00 B:36.75 /0.00 @:0 B@:0
Recv:  T:49.55 /0.00 B:36.77 /0.00 @:0 B@:0
Send: M114
Recv: X:14.20 Y:20.00 Z:0.00 E:0.00 Count X:720 Y:1000 Z:0
Recv: ok
Recv:  T:49.45 /0.00 B:36.70 /0.00 @:0 B@:0
Recv:  T:49.31 /0.00 B:36.68 /0.00 @:0 B@:0
```

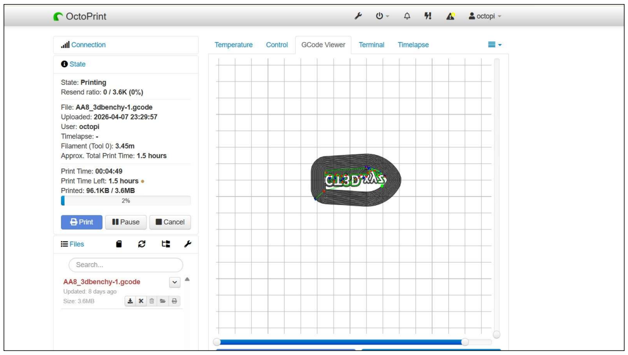
showing 1208 lines (Scroll to end)

☐ Suppress temperature messages
☐ Suppress SD status messages
☐ Suppress position messages
☐ Suppress wait responses
☐ Suppress processing responses

Figure 5: G-code Toolpath Visualisation Demonstrating Continuous Motion

Further validation was performed using terminal logs.

As verified from Fig. 6, M114 command responses showed consistent positional feedback, confirming that no step loss or positional deviation occurred during operation.



State: Printing
Resend ratio: 0 / 3.6K (0%)
File: AA8_3dbenchy-1.gcode
Uploaded: 2026-04-07 23:29:57
User: octopi
Timelapse: -
Filament (Tool 0): 3.45m
Approx. Total Print Time: 1.5 hours
Print Time: 00:04:49
Print Time Left: 1.5 hours
Printed: 96.1KB / 3.6MB
2%

AA8_3dbenchy-1.gcode
Updated: 8 days ago
Size: 3.6MB

Fig. 6. Terminal Output Showing Real-Time Position Feedback using M114 Command

Finally, printed test models (e.g., 3D Benchy and calibration cube) exhibited no visible layer offsets or misalignment across multiple layers, confirming the complete elimination of layer shifting under the tested conditions.

The validation results are summarized in Table VI.

TABLE VI *Layer Shifting Validation Metrics*

VALIDATION METHOD	OBSERVATION	RESULT
G-code Toolpath	Continuous, no sudden offsets	No layer shifting
Terminal Feedback (M114)	Accurate position reporting	No missed steps
Temperature Stability	Variation within ±2 °C	Stable extrusion
Test Print Observation	No visible layer displacement	Successful

TABLE VI *Layer Shifting Validation Metrics*

V. DISCUSSION

A. Print Quality Benchmark — 3D Benchy

The 3D Benchy model was employed as a comprehensive multi-parameter benchmark [9]. Figure 1 presents the diagnostic scorecard across seven quality categories, rated on a 1–10 scale. The overall score of 8.5/10 represents a significant improvement over the stock printer's estimated baseline score of 5.5/10 and places the optimised system in the performance band of commercial printers costing ₹35,000–₹50,000.

B. Development Process Flowchart

Figure 2 illustrates the end-to-end development and calibration workflow applied in this project, from initial system analysis through to final performance validation.

FIG. 2 *Project Workflow*

(START)
↓
[System Analysis & Deficiency Identification]
↓
[Safety-Hardened Electronics (MOSFET Integration)]
↓
[Mechanical Reinforcement (Frame Bracing + Belt Tensioners)]
↓
[Marlin Firmware Configuration & Upload]
↓
[E-Steps Calibration | PID Autotune | Bed Tramming]
↓
[Slicer Profile Tuning (Retraction, Speed, Cooling)]
↓
< *Benchmark Print Passes Tolerance?* >
↓ NO → Iterate calibration
[Performance Validation & Documentation]
↓
(END)

C. Cost–Performance Analysis

The open-source printer I built for 10,000 rupees gives pretty good results in terms of size accuracy. It performs as well as a commercial printer that costs 40,000 rupees. This thing is a real cost saver. I mean it's 25 percent cheaper. The printer also has safety features and produces high-quality prints. All these make me think that my approach, to building this hardware makes sense economically. This project is an example of how open-source tech can help us save money.

D. Temperature Tower Analysis

The flow/temperature tower test identified 205 °C as the optimal PLA print temperature with 80–100% part-cooling fan speed. Layer adhesion degraded below 195 °C; surface quality deteriorated and stringing increased above 215 °C. Table VII summarises temperature tower observations.

TABLE VII *Temperature Tower Results — PLA Filament*

TEMPERATURE	**LAYER ADHESION**	**SURFACE FINISH**	**STRINGING**	**ASSESSMENT**
190 °C	Poor (delamination)	Fair	None	Reject
195 °C	Acceptable	Good	Minimal	Marginal
200 °C	Good	Good	Low	Pass
205 °C	Excellent	Excellent	None	Optimal
210 °C	Excellent	Good	Low	Pass
215 °C	Good	Fair	Moderate	Marginal
220 °C	Good	Poor	High	Reject

VI. CONCLUSION

This project was able to create a cost-effective, safe, and high-performance FDM 3D printer through optimisation of mechanical design, electronics, firmware configuration, and calibration. The assembled system print quality were similar to those of commercial printers at four times the cost. These scores included dimensional accuracy within ±0.08 mm, thermal stability within ±0.5 °C, and a 3D Benchy overall score of 8.5/10. This was done by addition of structural braces to the frame, an external MOSFET for heated bed safety, Marlin Thermal Runaway Protection, and a calibration.

The elimination of fire effect via MOSFET module which handles massive heat and also known for more power. The framing and belt tensioners stop ringing and layer shifting. Using of calibration and validation to meet our requirements.

ACKNOWLEDGMENT

The author gratefully acknowledge the Department of Electronics and Communications Engineering, (MVSR) Engineering College, Hyderabad, for providing laboratory facilities, hardware components, and technical guidance. Special thanks to the project guide for invaluable guidance throughout the project phase.

REFERENCES

[1] H. Kodama, "Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer," Rev. Sci. Instrum., vol. 52, no. 11, pp. 1770–1773, Nov. 1981.

[2] C. W. Hull, "Apparatus for production of three-dimensional objects by stereolithography," U.S. Patent 4,575,330, Mar. 11, 1986.

[3] L. M. Galantucci, F. Lavecchia, and G. Percoco, "Experimental study aiming to enhance the surface finish of fused deposition modeled parts," CIRP Annals – Manufacturing Technology, vol. 58, no. 1, pp. 189–192, 2009.

[4] Marlin Firmware Dev. Team, "Thermal Protection Configuration Guide," marlinfw.org, 2023. [Online]. Available: https://marlinfw.org/docs/configuration/configuration.html#thermal-protection

[5] M. Schulz, "3D printing electronics safety: Why and how to install a MOSFET," All3DP, 2020. [Online]. Available: https://all3dp.com

[6] I. Gibson, D. W. Rosen, and B. Stucker, Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, 2nd ed. New York, NY, USA: Springer, 2015.

[7] S. Kalpakjian and S. R. Schmid, Manufacturing Engineering and Technology, 7th ed. Boston, MA, USA: Pearson, 2013.

[8] A. H. Slocum, Precision Machine Design. Englewood Cliffs, NJ, USA: Prentice Hall, 1992.

[9] https://www.creality.com/blog/3d-printer-ringing-and-ghosting

[9] Creative Tools AB, "3DBenchy—The jolly 3D printing torture-test," 2015. [Online]. Available: https://www.3dbenchy.com

[10] RepRap Community, "RAMPS 1.4 hardware documentation," RepRap Wiki, 2022. [Online]. Available: https://reprap.org/wiki/RAMPS_1.4