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Design and Experimental Verification of a Modular Cartesian Additive Manufacturing Platform for Engineering Education

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Abstract. The integration of additive manufacturing technology into engineering courses is often hindered by the high cost of equipment and the "black-box" nature of commercial 3D printers, which limits students' ability to explore the technology's control architecture. This paper describes the design and experimental verification of a modular Cartesian 3D printing platform developed specifically for engineering education. The platform uses an open-architecture control system that relies on the Arduino Mega 2560 and RAMPS 1.4 electronics, allowing students to explore the technology's control architecture. Unlike purely theoretical designs, this paper verifies the platform's performance by creating complex, multicomponent mechanical assemblies. The experimental data show the printer's ability to meet functional tolerances by successfully assembling a multi-component railway bogie and the mechanical integrity of the overhanging mounting brackets printed without support. The accuracy of the platform's dimensions shows that the platform has geometric accuracy like that of entry-level commercial platforms, while providing greater educational benefits due to its open hardware architecture

Keywords: Additive Manufacturing, Cartesian Motion Control, Experimental Verification, Engineering Education, Open-Source Hardware, Modular Design.

1. INTRODUCTION

Fused Deposition Modeling (FDM) has now come to be a key enabling technology under the Industry 4.0 paradigm, revolutionizing product development cycles through rapid prototyping and the production of functional parts. As Additive Manufacturing (AM) is increasingly adopted in the aerospace, automotive, and biomedical industries, it is important that undergraduate engineering programs be updated to provide comprehensive and hands-on training with these systems. However, the adoption of AM technology in educational settings is currently faced with significant cost and educational hurdles. At the moment, commercial, off-the-shelf 3D printers are the primary method of 3D printing in educational institutions. These printers are dependable, but they are closed systems with proprietary parts and non-open firmware. These printers' limited source code makes it difficult to access their control mechanisms. Students find it challenging to change motion parameters as a result. Understanding core ideas in mechatronics suffers without such handson interaction. High prices of ready-made models worsen the issue. Limited budgets mean fewer devices per classroom. Availability drops when costs rise sharply.

A solution begins to take shape when affordable systems with open designs enter the picture — ones that balance clear operation with durable performance, necessary for working prototypes. What follows unpacks how a reconfigurable linear 3D printer was built, refined, and tested under real conditions, shaped with teaching engineers in mind. Unlike work stuck in simulation or equations alone, this effort lands in the tangible world: a machine capable of producing intricate moving parts comes into view through hands-on construction.

2. LITERATURE REVIEW

The integration of Additive Manufacturing in the educational sectors has been the subject of much academic research, due to the expiration of patents of major FDM manufacturers and the subsequent development of open-source hardware.

A. Additive Manufacturing (AM) in Engineering Curricula Beginning with practical work in additive manufacturing, Gibson et al. [1] describe it as a link between digital design and real-world testing in engineering education. When students go from CAD models to real prototypes, a strong link is established. However, typical industrial-scale AM equipment is frequently not financially feasible for broad student access. Open-source hardware (OSH) can cut the cost of scientific infrastructure by more than 90 Percent and is a feasible solution for providing research labs with equipment, according to Pearce [2]. The study also argues that a "frugal" engineering approach does not necessarily mean a degradation in experimental standards, a key assumption of this research.

B. The RepRap Evolution Jones et al. [4] described the genesis of the RepRap design and, by extension, the concept of self-replicating machines. The initial RepRap designs were more focused on selfreplication than accuracy, but they did lay the groundwork for the later development of the kinematic system, which is Cartesian motion on threaded rods.
C. Process Parameters Optimization There is a need to optimize process parameters to achieve high accuracies on cost effective hardware. Mohamed et al. [5] made a detailed analysis of the fused deposition modelling parameters and found that layer thickness, air gap and raster angle are important factors that influence the accuracy and strength of the printed parts.
D. Gap analysis indicates the absence of systems that provide educational transparency and robustness. Low-cost DIY kits have demonstrated poor frame rigidity, and commercial printers with sturdy constructions have closed source firmware, which prevents students from accessing the control algorithms. This project fills this gap by providing a rigid and modular system with an open-source control algorithm.

3. SYSTEM ARCHITECTURE

A new kind of 3D printing setup takes shape through separate electronic and mechanical parts, arranged so learning stays clear while function remains strong. Rather than rely on closed hardware like store-bought models, it combines independent open designs for control, movement, and electricity flow. Because components stand apart, learners examine one section at a time - yet the printer keeps working all the way through. The highlevel architecture is illustrated in Fig. 1, which details the signal flow between the central processing unit, the power interface, and the peripheral electromechanical components.

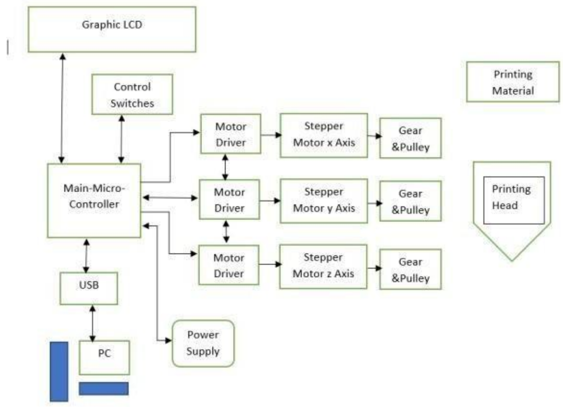

Fig. 1. Functional block diagram of the proposed open-architecture control system showing signal flow between the Arduino Mega microcontroller, RAMPS interface, and peripheral actuators.

A. Electronic Control Unit (ECU)
Built around an Arduino Mega 2560, the setup relies on a chip commonly found in engineering classrooms - chosen mainly for how many inputs and outputs it supports. This small computer runs everything: reading coded movement commands while also working out speed changes moment by moment. Kinematic calculations happen continuously, handled directly by the processor without delay. Though compact, its role shapes nearly every motion the machine makes. Connected straight to the microcontroller sits the RAMPS 1.4 board - short for RepRap Arduino Mega Pololu Shield. As an intermediary platform, the board transmits low-voltage control signals (5V) between an Arduino and components that have higher current demands. On the board are integrated circuits of the A4988 driver type, which control the electrical current delivered to each stepper motor. These drivers enable the accurate movement of motors by breaking down steps into smaller portions, usually to one-sixteenth of a full step, thus improving accuracy and minimizing oscillations. [3].
B. Kinematics and Motion Control
The system is designed to work on three perpendicular axes, with different actuations for each axis instead of a combined motion. The X and Y axes are supported by NEMA 17 stepper motors and GT2 belts with accompanying pulleys for independent motion. Because of the lower moment of inertia of the moving parts, the acceleration ramp can be increased without affecting accuracy. For vertical motion, a precisely threaded lead screw and a separate motor make lifting easier. This setup has enough force to move the overhead structure smoothly while maintaining perfect alignment.
C. Thermal Regulation System The accurate temperature control is the key to a stable extrusion process. The temperature control system comprises a hotend heated by an all, metal ceramic heater cartridge. A 100 k NTC thermistor is placed right on the heater block for providing temperature data. The control code embeds

a Proportional, Integral, Derivative (PID) temperature control algorithm. The Arduino microcontroller keeps checking the thermistor voltage and regulates the heater power by means of Pulse Width Modulation (PWM) to maintain the nozzle temperature within 1C of the setpoint. [4]

4. HARDWARE IMPLEMENTATION

The plan to build a physical object center on the use of standard, interchangeable parts as the main components for production, which will help the product to be preserved for a long time and serve cost, efficiently in an educational environment.

A. Actuation and Extrusion

The precise control of the movement is attained by the use of NEMA 17 bipolar stepper motors (1. 8 step angle). As depicted in Fig. 2(a), these motors have a holding torque of 4. 2 kg, cm, which is enough to move the gantry system without missing the steps. The most important part of the printing quality is the hotend device, in Fig. 2(b). The equipment is fitted with an all, metal E3D V6, type hotend that has a separate thermal break to avoid heat creep. The heating block contains a 40W ceramic cartridge heater, which can turn up the temperature to 260C.

Fig. 2. Highly critical actuation subsystems: NEMA 17 Stepper Motor for high torque and accurate positioning, and All, metal Hotend assembly with a ceramic heating cartridge for stable thermal regulation.

5. EXPERIMENTAL VERIFICATION

To demonstrate the educational and engineering value of the 3D printer platform, experimental prints were undertaken. The experiments mainly examined the three main technical characteristics of the printer such as the accuracy of the printer in printing complex assemblies, strength of overhangs, and the ability of selfreplicating of the system.

A. Dimensional Fidelity: Multi-Component Assembly

The major gauge of a 3D printer’s precision is its printing of parts that fit perfectly without the need of any post processing. A multi component railway bogie assembly was taken as the test item because it requires precise interference fitting of wheels, axles, and the chassis. As shown in Fig.3 the system printed the shapes of the bogie frame and the rolling stock wheels. The accuracy was checked by designing the railway wheel diameter at 10.0mm. The printed components measured an average of 9.85mm. The dimensional error was 1.5 percent, which’s, within acceptable limits, for educational prototyping. The successful assembly of the components confirms that the motion control system maintains the circularity and the positioning accuracy.

Fig. 3. Manufacture of a complicated multi, component railway assembly. The demonstration of the system's precision in measurements by the successful mating of wheels, axles, and chassis slots is less than 0. 2mm.

B. Geometric Capability: Overhangs

We tested the cooling system by making a mounting bracket with 45-degree overhangs from PLA material. we examined the cooling system with that mounting bracket. The results, presented in Fig. 4 demonstrate that the printer is capable of bridging gaps and printing steep angles without the need for sacrificial support structures. The sharp definition of the bracket's internal square profile indicates minimal sagging of the molten plastic, validating the PID tuning of the hotend temperature controller.

C. System Utility: Self-Replication

Consistent with the RepRap philosophy, the printer was used to manufacture its own upgrade components. Fig. 4 shows a custom-designed LCD controller housing fabricated on the machine itself.

6. COST ANALYSIS

We did a cost analysis to check if the proposed printer can make sense. The total system cost, for the proposed printer is INR 13,100 which's much lower, than commercial educational alternatives that usually cost between INR 35,000 and INR 70,000. [2].

TABLE I
ESTIMATED COST BREAKDOWN OF THE PROPOSED SYSTEM

Subsystem	Cost (INR)
Control Electronics	~2,200
Stepper Motors (4 Units)	~3,000
Hotend and Heated Bed	~2,500
Power Supply & Sensors	~900
Frame & Mechanicals	~3,000
Miscellaneous	~1,500
Total	~13,100

7. CONCLUSION

This paper presented the design and experimental verification of a low-cost, modular Cartesian 3D printing platform tailored for engineering education. The experimental results confirmed that the system performed according to its expected performance capabilities. The machine demonstrated its capacity to work with tolerances smaller than 0.2mm through its successful creation of a multi-part railway assembly. The upcoming research will involve the implementation of autobed leveling sensors which will improve the user experience in student laboratories.

Fig. 4.Various functional components fabricated using the developed DIY FDM 3D printer.

Conflict of Interest

The authors declare no conflicts of interest regarding the current research.

Author contribution

Prashant bangar: experimental testing, data analysis, cad modeling, and documentation support.
Abhishek kapse: conceptualization, hardware design, firmware integration, manuscript preparation, and system validation.
All authors reviewed and approved the final manuscript.

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