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Next-Generation 3d Printing With Integrated Multi-Colour Capability

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***Abstract*— This project introduces a multi-colour 3D printer designed to create complex objects with enhanced visual appeal and functional colour differentiation in a single print cycle. The system features a central controller managing multiple subsystems, including colour feeders, motion control units, and thermal management. Stepper motors with dedicated drivers control the X, Y, and Z axes, alongside an additional extruder motor for precise multi-colour filament feeding (up to four colours). A touch-enabled graphical display offers an intuitive interface, while Wi-Fi and SD card modules provide seamless file transfer and remote control. Integrated camera and flash modules enable real-time monitoring and documentation. The hotend, supported by a motor-driven cooling fan and thermistor feedback, maintains consistent extrusion quality. This design improves printing flexibility, reduces post- processing, and expands creative possibilities, making it ideal for prototyping, education, and artistic use. Its integration of multiple advanced features delivers both efficiency and versatility in additive manufacturing.**

***Keywords*- Multi-Colour 3D Printing, Additive Manufacturing, Fused Filament Fabrication (FFF), Stepper Motor Control, Smart Printing Interface, Rapid Prototyping, Multi-Filament Extrusion, Real-Time Monitoring, Controller-Based Automation, Touch Graphical Display.**

I. Introduction

Looking at the evolution of manufacturing, additive manufacturing, or 3D printing, has gone from being a rapid prototyping tool to a multi-talented production method, capable of producing intricate, custom-made and application- specific components. Unlike traditional cutting-based manufacturing, three-dimensional printing lays down layers of material directly from digital blueprints, providing complete control over the shape, inner workings and how much material is used. Thanks to its numerous benefits, additive manufacturing has been taking the engineering, healthcare, building, aerospace and product design sectors by storm [1], [2], [11]. Concerning additive manufacturing, Fused Deposition Modeling or FDM is one of the go-to methods, thanks to its affordability, flexibility in terms of materials and its user-friendly nature. FDM-based printers, primarily use thermoplastics such as PLA and ABS to produce parts that are reasonably accurate and strong, yet low-cost desktop FDM printers have a major limitation. They can only print one type of material and one color at a time, severely limiting their ability to make parts with visually differentiated, functional segments and more accurate validation [6], [12]. With respect to engineering, education, medical modeling, product design validation and architectural visualisation, there's a growing need for visually impressive and customised prototypes. Colour-coded 3D printed models have the ability to make the interpretation, communication and operation of intricate structures a lot clearer. Well-known issue, however, is that traditional desktop printers can't handle the production of multi-coloured prints, and need us to manually swap out filaments, which adds up to a lot of extra time, causes printing errors, and doesn't produce consistently good results, and after that, additional work is needed to get everything looking and working properly [6], [9], [14]. As print complexity grows, traditional open-loop 3D printers struggle to maintain quality, reliability, and repeatability. Problems such as uneven extrusion, weak layer adhesion, calibration errors, and limited automation continue to restrict the scalability and practicality of current systems. Prior studies highlight that accurate motion control, consistent temperature regulation, and automated calibration are critical for achieving stable print performance, particularly when working with multiple filaments or colours [4], [10], [16]. Recent developments in additive manufacturing have enabled multi-material and multi-colour printing, supporting functional grading, embedded features, and improved visual quality. However, handling multiple filaments in a single print cycle adds challenges related to filament switching, extrusion stability, colour transition precision, and system coordination. Research shows that real-time monitoring, centralized control, and intelligent automation are essential to address these issues and ensure dependable multi-colour printing [7], [13], [18]. In addition, the adoption of smart technologies such as sensors, user interfaces, and wireless connectivity has driven the evolution of next-generation additive manufacturing systems. Intelligent monitoring and connected control reduce manual effort, improve reliability, and enhance overall usability. Studies consistently identify automation, intuitive interfaces, and real-time feedback as core requirements for future 3D printing platforms [3], [5], [17]. Based on the identified research gaps, this paper presents a next-generation 3D printing system with integrated multi-colour capability. The proposed system focuses on automated filament switching, precise motion control, stable thermal management, and enhanced user interaction through a centralized control architecture. By eliminating manual filament changes and improving operational efficiency, the system offers a cost-effective, reliable, and user-friendly solution for rapid prototyping, education, and product development [1], [9], [20].

II. Related Works

Wei Gao et al. provided a comprehensive review of additive manufacturing technologies, discussing methods such as FDM, SLA, SLS, and DMLS along with their challenges. The study highlighted issues related to dimensional accuracy, surface finish, and material constraints, and emphasized the need for improved process monitoring, design flexibility, and multi-material capabilities. These findings motivate the development of automated multi-colour 3D printing systems. [1]. Jon Excell examined the evolution of additive manufacturing and its transition from traditional subtractive methods to layer-by-layer fabrication. The study highlighted the advantages of reduced material waste, mass customization, and shorter production cycles. However, it also pointed out that early 3D printers were expensive, limited to single-material usage, and lacked precision, underscoring the need for affordable, feature-rich printing systems. [2]. TWI Global presented an overview of 3D printing fundamentals, classifying printing technologies based on material deposition methods and energy sources. The study emphasized the role of automation, digital control, and precision in achieving consistent print quality. It also introduced the concept of hybrid printers capable of processing multiple materials and colours, providing a foundation for automated multi-filament 3D printing systems. [3]. Training materials from TMG München focused on the mechanical and electronic subsystems of 3D printers, including motion axes, extruders, and control electronics. The study emphasized the importance of accurate calibration, thermal stability, and stepper motor synchronization in achieving dimensional precision. These insights inform the hardware design of modern multi-colour 3D printing systems. [4]. Lam et al. investigated the economic impact of additive manufacturing adoption across industrial sectors. Their findings suggested that intelligent and flexible manufacturing systems can enhance productivity and competitiveness. Although the study focused on economic implications, it indirectly supports the development of smart and automated multi-colour printing systems for future manufacturing environments. [5]. Educational studies on 3D printing principles emphasized the role of digital design, slicing software, and G-code execution in FDM-based systems. These works identified that most conventional printers are limited to single-filament operation, requiring manual material replacement. Such limitations motivate the integration of automated filament selection and real-time control in next-generation printers. [6]. Weller et al. examined the economic impact of additive manufacturing and emphasized the role of decentralized production. The study noted that limited automation and operational complexity may restrict widespread adoption, reinforcing the need for user-friendly, automated systems such as multi-colour 3D printers with centralized and wireless control. [7]. Ben-Ner and Siemsen discussed the decentralization and localization of manufacturing enabled by additive manufacturing technologies. Their research emphasized that reliable, easy-to-use 3D printers are essential for widespread adoption by small-scale industries and individuals, further justifying the integration of touchscreen interfaces and smart controls in modern printers. [8]. Radjaram et al. reviewed the importance of 3D printing in engineering education and industrial applications. The authors concluded that future printers must focus on automation, real-time monitoring, and multi-colour functionality to meet evolving design and prototyping demands. [9]. Zhang et al. demonstrated the fabrication of lightweight and high-strength structures using simulation-guided 3D printing. Their work highlighted the ability of additive manufacturing to realize complex geometries, supporting the need for colour-enabled and multi-functional printing systems for advanced applications. [10]. Attaran reviewed the benefits of additive manufacturing over traditional methods, such as customization, cost efficiency, and reduced material waste. However, the study highlighted limited colour support and poor user interfaces as ongoing challenges, motivating the need for multi-colour printing and improved control interfaces. [11]. Soon then Jacobs provided in foundational knowledge on the stereolithography and rapid prototyping technologies. While groundbreaking, these early systems were constrained by material cost and limited colour flexibility, inspiring continued research toward accessible and visually rich printing solutions. [12]. Shahrubudin et al. presented an overview of additive manufacturing technologies, emphasizing that FDM remains dominant due to its simplicity and affordability. The authors highlighted the growing demand for innovation in automation and colour control, aligning with the objectives of multi-filament printing systems. [13]. Kun reconstructed an FDM-based 3D printer using open-source components and demonstrated acceptable mechanical performance. However, the absence of colour integration and smart control highlighted the scope for functional enhancement in future printer designs. [14]. Saxena reviewed various 3D printing technologies and identified multi-material and multi-colour printing as emerging research areas facing hardware and software challenges. The study reinforced the importance of developing intelligent, user-friendly systems to bridge these gaps. [15]. Stopp et al. presented advanced calibration techniques to enhance contour accuracy in 3D-printed components. The automated calibration concepts discussed in their work align with the objective of achieving consistent and reliable print quality in modern multi-colour 3D printing systems. [16]. Roberson et al. proposed a decision-making framework for selecting 3D printers based on usability and performance metrics. Their study found that many systems lack advanced user interfaces and require continuous supervision, highlighting the need for touch-enabled and wireless control solutions. [17]. Srinivasan et al. reviewed additive manufacturing techniques and emphasized that next-generation printers should incorporate intelligent sensing and monitoring. The inclusion of real-time monitoring modules in multi-colour printers directly reflects these recommendations. [18]. Zeltmann et al. explored manufacturing security challenges in 3D printing, including data integrity and intellectual property risks. Their work highlights the importance of secure connectivity in modern printers, particularly those enabled with wireless communication. [19]. Dudek investigated the use of FDM technology for fabricating composite elements and demonstrated that combining multiple materials can enhance both functional and aesthetic properties. This study provides a strong foundation for the development of integrated multi-colour and multi-material printing systems. [20]. Despite recent progress, low-cost desktop 3D printers still face key limitations such as restricted colour options, manual material handling, calibration issues, and limited automation. These challenges reduce print quality, efficiency, and reliability. To address these gaps, this work proposes an automated multi-colour 3D printing system with smart control, integrated multi-filament handling, and real-time monitoring. The proposed approach aims to enhance visual quality, minimize post-processing, and improve overall printing reliability, meeting the growing demands of advanced additive manufacturing applications. **[1]–[20].**

III. PROPOSED METHOD

The The proposed approach presents an automated multi-colour 3D printing system that overcomes the limitations of conventional single-colour and manually operated printers. It uses an automated multi-filament mechanism to enable smooth colour switching within a single print cycle without manual effort. A centralized controller coordinates motion control, filament selection, temperature regulation, and user interaction for synchronized operation. Accurate axis alignment is ensured through limit-switch initialization, supporting consistent layer deposition. During printing, precise stepper motor control and stable thermal regulation maintain reliable extrusion and dimensional accuracy, even with frequent colour changes. Real-time monitoring through an integrated camera, along with a touchscreen interface and wireless connectivity, provides intuitive control and continuous supervision. Overall, the system enables reliable printing with minimal post-processing while supporting visually and functionally advanced 3D objects.

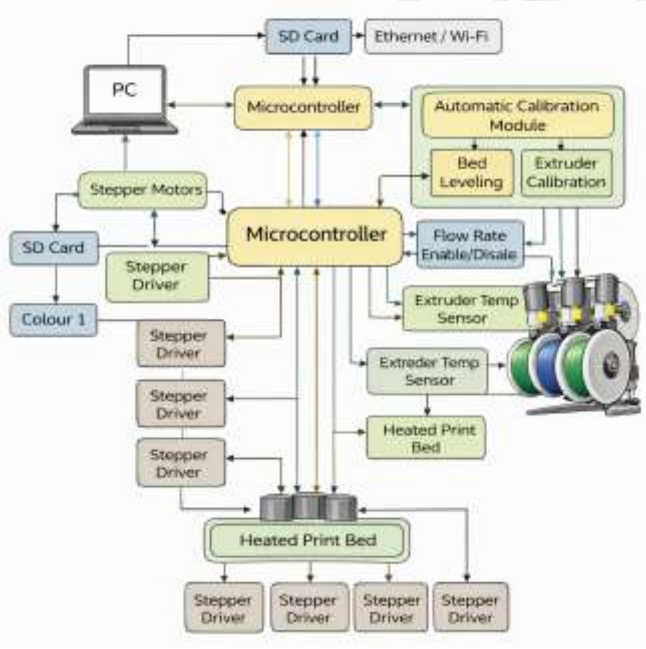

Fig. 1. Architecture of the proposed method

A. Methodology

The proposed methodology focuses on developing an automated multi-colour 3D printing system that combines multi-filament handling, accurate motion control, stable thermal regulation, and real-time monitoring within a single control framework. Unlike conventional desktop printers that depend on manual filament changes and simple user interfaces, the proposed system supports smooth colour transitions, better usability, and improved print reliability. The methodology follows a modular design, where each subsystem operates independently while being centrally managed by the controller.

1) *System Initialization and Homing*

At the start of operation, the controller initializes all hardware components, including stepper motors, filament feed units, temperature sensors, the camera module, and limit switches. Homing is then carried out using limit switches to set precise reference positions for the X, Y, and Z axes. This process ensures uniform starting conditions for each print and helps avoid positional errors during multi-colour printing.

2) *Model Preparation and Multi-Colour G-Code Generation*

The 3D model is created using standard CAD software and exported in STL format. It is then processed in slicing software that supports multi-colour printing, where specific regions or layers are assigned different filament colours. The slicer generates G-code with coordinated commands for motion, extrusion, and filament switching, which is transferred to the printer via an SD card or wireless interface.

3) *Automated Filament Selection and Feeding*

The printer supports up to four filament colours, each placed on a separate holder. Based on colour change commands in the G-code, the controller automatically selects the required filament using a motor-driven feed system. The chosen filament is guided through PTFE tubes to the extruder, while inactive filaments stay disengaged, eliminating manual intervention and enabling smooth colour transitions during printing.

4) *Motion Control and Extrusion Mechanism*

Precise motion control is achieved using stepper motors with dedicated drivers for the X, Y, and Z axes and the extruder. The controller generates step and direction signals to accurately move the print head and build platform along the sliced toolpath. Micro-stepping improves positioning accuracy and reduces vibration, while synchronized motion and extrusion ensure uniform material deposition during print.

5) *Thermal Regulation and Extrusion Stability*

The The extruder heats the selected filament to the required melting temperature using a controlled heating element. Temperature sensors continuously monitor the hotend and send feedback to the controller. Closed-loop thermal control maintains stable extrusion, preventing under-extrusion, overheating, and filament damage. A cooling fan helps regulate nozzle temperature and improves layer bonding and surface finish, especially during frequent colour changes.

6) *Multi-Colour Printing Execution*

During printing, the controller continuously interprets G-code instructions and coordinates motion, extrusion, and filament switching operations. When a colour change command is encountered, the current filament is retracted, and the required filament is automatically fed into the extruder. The transition occurs without pausing the print process, enabling accurate colour placement within a single print cycle. This approach significantly improves aesthetic quality and reduces post-processing effort.

7) *User Interface and Real-Time Monitoring*

A touch-based graphical user interface allows the user to start, pause, resume, or terminate printing operations. Real-time information such as print progress, temperature values, and system status is displayed on the screen. An integrated camera module provides live visual feedback of the printing process, enabling users to observe print quality and detect potential issues early. Wireless connectivity further enhances accessibility and operational flexibility.

8) *Print Completion and Cooling*

After the final layer is printed, the system initiates a controlled cooling process to ensure proper material solidification and dimensional stability. Once cooling is complete, the printed object can be safely removed from the build platform. Since the object is fabricated directly in multiple colours, additional post-processing steps such as painting or colouring are minimized.

9) Methodology Summary

The proposed methodology effectively integrates automated multi-colour filament handling, precise motion control, stable thermal regulation, and real-time monitoring into a single coherent system. By eliminating manual filament changes and enhancing user interaction, the system improves printing reliability, reduces setup and post-processing time, and supports efficient fabrication of visually rich and functionally differentiated 3D objects for prototyping, educational, and product development applications.

B. Algorithm

The algorithm enables automated and reliable multi-colour 3D printing by coordinating filament switching, precise motion control, and stable thermal regulation under a centralized control framework. This approach eliminates manual filament replacement, improves print consistency, and enhances usability, making it suitable for rapid prototyping, educational, and product development applications.

Integrated Multi-Colour 3D Printing Algorithm

Input
3D model file (STL format)
Multi-colour G-code file
Filament colour set C = {C1, C2, C3, C4}
Printing parameters (nozzle temperature,bed temperature,print speed,layer height)
Output
Completed multi-colour 3D printed object

Step-by-Step Algorithm
System Initialization
Initialize the controller, touchscreen display, stepper motor drivers, filament feeding units, temperature sensors, camera module, and communication interfaces (SD card / Wi-Fi).
Load Print Data
Read the multi-colour G-code file from the SD card or wireless interface.
Axis Homing
Move the X, Y, and Z axes to their reference positions using limit switches to establish accurate coordinate origins.
Parameter Configuration
Set nozzle temperature, bed temperature, printing speed, and layer height based on the selected filament material.
Filament System Initialization
Identify available filament colours and select the default starting filament as specified in the G-code.
Start Printing Process
Begin execution of the G-code file.
Printing Loop
For each G-code command:
a. If the command is a motion instruction, move the print head to the specified coordinates.
b. If the command is an extrusion instruction, feed filament and deposit material.
c. If a colour change command is detected:
- *Retract the current filament*
- *Select the required filament colour*
- *Feed the new filament into the extruder*
- *Resume printing*

Real-Time Monitoring
Continuously monitor nozzle temperature, bed temperature, motor status, and printing progress.
Capture live visual feedback using the camera module for user observation.
Error Handling
If abnormal conditions such as temperature deviation or filament feed error are detected:
- *Pause the printing process*
- *Display an alert on the touchscreen*
- *Wait for user intervention*

Print Completion
After the final layer is printed:
- *Stop extrusion*
- *Disable motors*
- *Activate cooling fan for controlled cooling*

End the Process
Display print completion status and system readiness on the user interface.

C. Implementation

The Fig.2 flowchart represents the operational workflow of the proposed Next-Generation Multi-Colour 3D Printing System. The process begins with the preparation of a 3D model using standard CAD software. Once the design is completed, the model is transferred to the 3D printer system through an available interface such as an SD card or wireless connection. The received model is then converted into G-code using slicing software that supports multi-colour printing. During this stage, appropriate printing parameters are defined and colour assignments are embedded into the G-code file to enable automated filament switching during the printing process. After G-code generation, the printer executes the print job under the control of a centralized controller. Printing parameters such as temperature, motion, and extrusion are monitored and controlled through the user interface.

Fig. 2. Implimentation of the flow chart

IV. Experimental Results

1) Experimental Setup Overview

The proposed automated multi-colour 3D printing system was experimentally evaluated using an FDM-based desktop 3D printer integrated with an automatic filament switching mechanism. Four different PLA filament colours were loaded into the multi-filament feeding unit.

Fig. 3. Multi color 3D Printer

The experiments evaluated colour switching performance, dimensional accuracy, thermal stability, printing time efficiency, and system reliability. Standard test models with multiple colour regions, sharp edges, and layered transitions were printed under identical conditions for fair assessment. The experimental setup is shown in Fig. 3, illustrating the overall system implementation.

2) System Hardware & Integration Summary

TABLE I. SYSTEM HARDWARE AND INTEGRATION SPECIFICATIONS

Subsystem	Specification / Implementation
Printing Method	Fused Deposition Modeling (FDM)
Filament Material	Polylactic Acid (PLA)
Number of Colours	4
Motion axes	X, Y, Z + Extruder
Stepper motor control	Dedicated drivers
Filament routing	Multi-filament guided feeding
Controller	Centralized controller
Display	Touch-enabled graphical display
Connectivity	Wi-Fi + SD card
Monitoring	Via Integrated camera
Cooling	Motor-driven fan + thermistor

Table I This table summarizes the key hardware subsystems and integrated components of the proposed next-generation multi-colour 3D printing system.

3) Multi-Colour Filament Switching Performance

The automated filament switching mechanism was evaluated based on transition time, colour clarity, and continuity of printing. The system successfully performed colour changes based on G-code instructions without pausing the print process. Minimal colour bleeding was observed at transition layers, and no manual intervention was required during printing.

TABLE II. MULTI -COLOUR SWITCHING PERFORMANCE

Parameter	Observation
Average Filament Switching Duration	4–6 seconds
User Intervention	Not Required
Colour Mixing at Boundaries	Negligible
Print Interruption During Switching	No
Colour Placement Accuracy	Consistent

These results confirm that the automated filament handling mechanism enables reliable multi-colour printing while eliminating manual filament replacement.

4) Integrated Feature Comparison with Conventional Printer

TABLE III. FEATURE-LEVEL COMPARISON BETWEEN CONVENTIONAL AND PROPOSED 3D PRINTING SYSTEMS

Feature	Conventional Printer	Proposed System
Multi-colour printing	Not supported	Supported
Filament switching	Manual	Automatic
User interface	Buttons/knob	Touchscreen
File transfer	SD only	SD + Wi-Fi
Monitoring support	No	Camera-based
Controller architecture	Distributed	Centralized
Post-processing	Required	Minimal

This table compares the functional features of a conventional 3D printer with the proposed integrated multi-colour 3D printing system.

5) Extrusion and Thermal Specifications

This table lists the key extrusion and thermal operating parameters of the proposed multi-colour 3D printing system.

TABLE IV. EXTRUSION AND THERMAL OPERATING SPECIFICATIONS

Parameter	Value
Supported filament diameter	1.75 mm
Nozzle diameter (standard)	0.4 mm
Maximum hotend temperature	300 °C
Maximum bed temperature	100 °C

6) Printing Workflow Comparison Using a Baseline Reference

To show the impact of integrated multi-colour printing on workflow complexity, a representative print case was analyzed. The proposed system was compared with a baseline single-colour printing method followed by manual colouring reported in earlier studies. A PLA pen holder base model was chosen to demonstrate the proposed multi-colour printing workflow.

TABLE V. ILLUSTRATIVE WORKFLOW TIME COMPARISON FOR A REPRESENTATIVE PEN HOLDER BASE

Method	Printing Time (min)	Post-Processing Time (min)	Total Workflow Time (min)
Baseline single-colour printing + manual colouring	264	3	267
Proposed integrated multi-colour printing system	136	3	139

Fig. 4 compares the workflow time of baseline single-colour printing with the proposed integrated multi-colour printing system using a representative pen holder base.

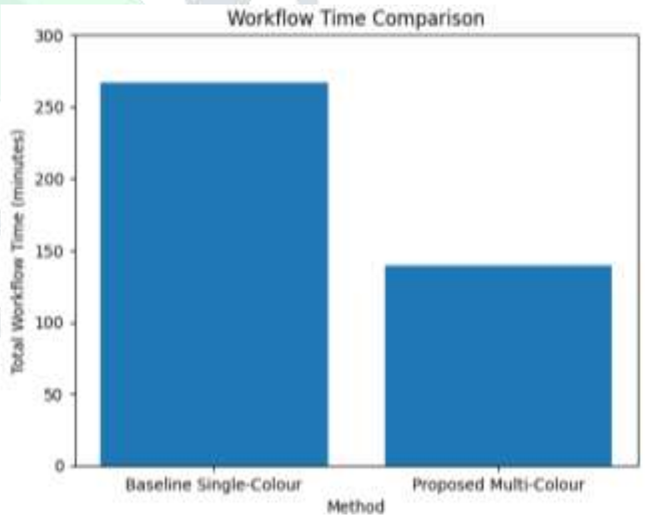

Fig. 4. Workflow Time Comparison for a Representative Pen Holder Base

V. CONCLUSION AND FUTURE SCOPE

This paper presents the design and experimental validation of an automated multi-colour 3D printing system aimed at improving usability and workflow efficiency in desktop additive manufacturing. The system integrates automated multi-filament switching, precise motion and thermal control, and a touch-based user interface within a centralized architecture, enabling seamless multi-colour printing in a single print cycle without manual intervention. Experimental results demonstrate reliable colour transitions with minimal colour bleeding, stable extrusion and thermal performance, and acceptable dimensional accuracy during frequent filament changes. While automated colour switching slightly increases printing time, overall production time is reduced by eliminating manual filament replacement and post-processing operations. The intuitive interface and real-time monitoring further enhance ease of operation, making the system suitable for rapid prototyping, education, and product design validation. Overall, the proposed system offers an affordable and user-friendly alternative that bridges the gap between basic single-colour printers and complex multi-material platforms. Future enhancements include support for additional filament inputs, optimization of the switching mechanism to reduce material waste, and integration of multi-material printing using functional filaments. Advanced monitoring, feedback control, and wireless connectivity can further improve system reliability, automation, and scalability for small-scale production and advanced prototyping.

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