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DEVELOPMENT OF A COMPACT AND SUSTAINABLE CNC MILLING MACHINE FOR PCB PROTOTYPING

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ABSTRACT

The growing demand for printed circuit boards (PCBs) in various electronic applications calls for sustainable and accessible advancements in PCB manufacturing. Traditional fabrication methods are often manual, resource-intensive, and lack precision, making them unsuitable for rapid prototyping in educational or low-budget environments. This study presents a cost-effective desktop PCB milling machine prototype designed to support sustainable learning and innovation by enabling students and makers to produce high-quality PCBs in-house. The machine utilizes open-source Marlin firmware and is modeled using SolidWorks. It features mesh bed leveling, gantry movement, and real-time monitoring via the TFT43 V3.0 touchscreen integrated with the BigTreeTech SKR Mini E3 V3.0 control board, enhancing operational efficiency and user experience. Testing demonstrated the stepper motors high positional accuracy of $99.49\% \pm 0.1\%$ on both X and Y axes, confirming the machine's reliability for precise PCB layout production. This project promotes sustainable engineering education and provides a practical tool to advance digital fabrication and lifelong learning in the Industry 4.0 era.

Keywords: PCB milling machine, sustainable engineering education, open-source firmware, digital fabrication; Industry 4.0

INTRODUCTION

The demand for printed circuit boards (PCBs) continues to rise due to their role as essential components in electronic devices across various industries. Conventional fabrication methods, which involve heat transfer and chemical etching, are time-consuming, inconsistent, and environmentally harmful. As a sustainable alternative, CNC-based PCB milling enables precise, automated removal of copper layers through computer-controlled operations. Commercial machines, such as the Wegstr 3-axis system, demonstrate the feasibility of this approach by offering high-precision milling and drilling for rapid

prototyping.

1.2 Problem Statement

Conventional PCB fabrication methods are inconsistent, time-consuming, and highly dependent on operator skill. They also involve hazardous chemicals, posing safety and environmental risks while increasing the likelihood of defects. Desktop PCB milling provides a safer, faster, and more sustainable alternative, reducing human error and eliminating chemical use.

1.3 Objectives

This project aims to develop a desktop PCB milling machine that offers a safer, more sustainable, and more efficient alternative to conventional chemical-based fabrication. The objectives are:

1. To design and prototype the machine with features that support precision and sustainability.
2. To implement mesh bed leveling for consistent first-layer calibration and reduced waste.
3. To evaluate performance in terms of accuracy, reliability, and usability compared with manual methods.

1.4 Project Scope

The prototype was designed in SolidWorks and fabricated mainly using 3D-printed parts to minimize cost and time. The compact machine (30 × 30 × 30 cm, milling bed 15 × 15 cm) integrates a Cartesian motion system, Genmitsu GS-775M spindle motor, and open-source Marlin firmware. A TFT35 V3.0 touchscreen provides the user interface, while the system incorporates spindle control and mesh bed leveling to enable precise PCB prototyping.

METHODS

The PCB milling machine was first modeled in SolidWorks and fabricated using 3D-printed parts to minimize cost and allow rapid redesign. The compact structure (30 × 30 × 30 cm, bed size 15 × 15 cm) integrates motion along three Cartesian axes with functional spindle control and mesh bed leveling.

Key hardware components include NEMA 17 stepper motors with microstepping for high positional accuracy, the Genmitsu GS-775M spindle motor capable of speeds up to 12,000 RPM, and the BigTreeTech SKR Mini E3 V3.0 control board with integrated TMC2209 drivers for quiet and precise operation. A TFT43 touchscreen was employed as the user interface, providing real-time

monitoring and control. These components were selected for their affordability, wide availability, and proven reliability in CNC and 3D printing applications.

For software, Marlin open-source firmware was configured through Visual Studio Code to define axis steps, spindle parameters, and mesh bed leveling. PronterFace was used as the host interface for sending G-code, calibration, and machine testing. Together, the hardware and software integration ensured flexible control, iterative fine-tuning, and sustainable PCB milling performance.

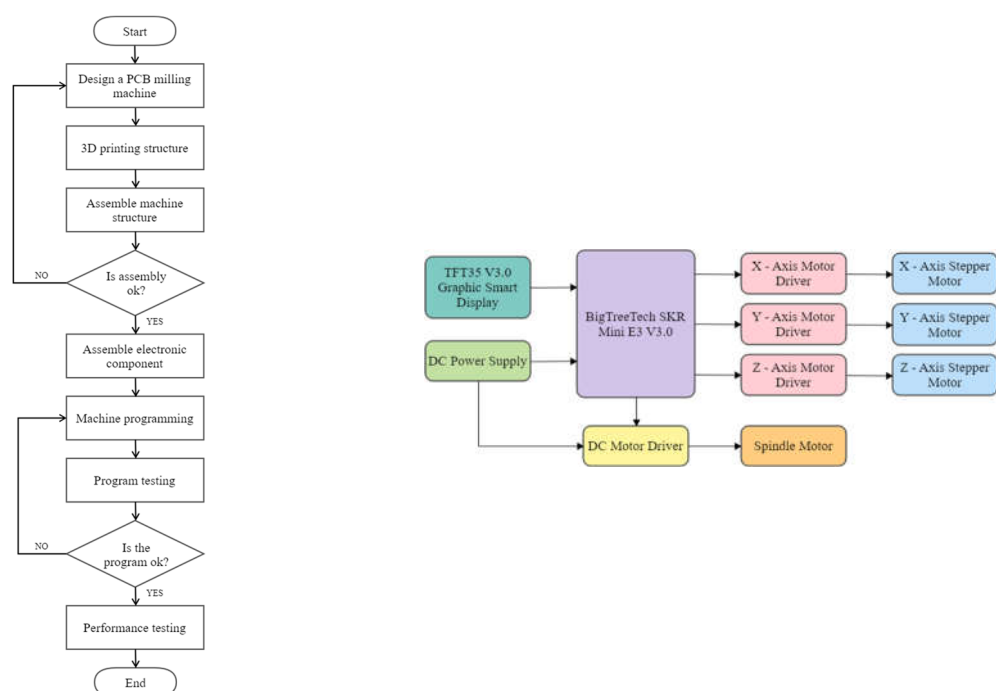


Figure 3.1: Flowchart and block diagram of the project design.

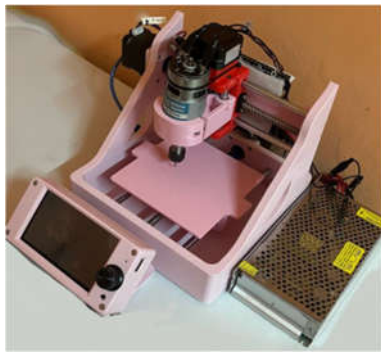
RESULTS AND DISCUSION

The prototype was successfully assembled using 3D-printed PLA components, a gantry-based structure, and linear rails, ensuring stability and smooth axis movement. The SKR Mini E3 V3.0 control board with TMC2209 drivers provided efficient motion control, while the TFT43 touchscreen enabled intuitive parameter adjustment.

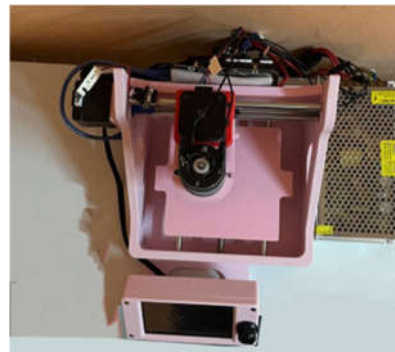
Performance testing validated the functionality of the main subsystems. The stepper motors demonstrated reliable operation with high positional accuracy, averaging $99.49\% \pm 0.1\%$ across both X and Y axes. Mesh bed leveling, implemented through manual calibration, improved surface uniformity and resulted in consistent milling depths, reducing rework and waste. The Genmitsu GS-

775M spindle motor operated smoothly up to 12,000 RPM, maintaining stable performance under light machining loads.

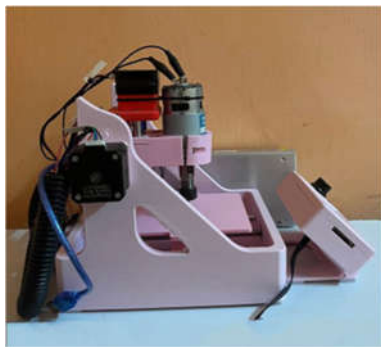
The integration of PronterFace software allowed direct G-code communication and calibration, complementing the touchscreen interface for flexible operation. Combined, these results confirm that the prototype achieves precise PCB prototyping with repeatable accuracy, supporting its suitability for sustainable, small-scale electronic fabrication.



(a)



(b)



(c)



(d)

Figure 4.1.: Machine design in (a) isometric, (b) top, (c) side, and (d) front view

Table 4.3.: Performance results of randomized X- and Y-Axis testing

Test	Result	Outcome
Stepper motor accuracy	99.49% $\pm$ 0.1%	Reliable axis precision
Mesh bed leveling	Uniform surface mapping	Improved cutting consistency
Spindle motor (GS-775M)	Up to 12,000 RPM, stable under load	Effective for PCB milling

CONCLUSION

The developed desktop PCB milling machine proved effective for prototyping, combining a compact 3D-printed structure with open-source hardware and software. Key components, including the SKR Mini E3 V3.0 control board, NEMA 17 stepper motors, GS-775M spindle motor, and TFT43 touchscreen, enabled reliable performance with high accuracy. Stepper motors achieved an average precision of **99.49% $\pm$ 0.1%**, while mesh bed leveling improved surface consistency and milling quality.

The system eliminates hazardous chemical etching, supports sustainable, low-waste fabrication, and provides a practical tool for education and small-scale innovation. Future work will focus on refining calibration methods and enhancing advanced features to further improve usability and performance.

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