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PCB Circuit Printing Machine Using Arduino Uno R3 and CNC Shield

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Abstract: The rapid advancement of electronics technology necessitates a modern, safe, and user-friendly approach to printed circuit board (PCB) fabrication. This study aims to develop a prototype PCB milling machine based on an open-source control system utilizing Arduino Uno R3, CNC Shield V3 and GRBL firmware. The system is designed to replace the hazardous chemical etching method with a safer, three-axis milling process. A Waterfall research design model was applied and three main tests were conducted: continuity, voltage supply, and system functionality. Findings demonstrate that the machine performs reliably in terms of power distribution, motor movement, PCB engraving and Bluetooth control. Improvements were made in calibration values and cutting tool selection to ensure optimal engraving quality. The results indicate the effectiveness of this machine in fulfilling the technical and safety requirements of TVET education, while also exposing students to real-world industrial automation systems. Therefore, this machine offers an innovative and low-cost alternative to conventional PCB manufacturing methods in technical education institutions.

Keywords: CNC machine, Arduino Uno, Bluetooth HC-05, GRBL firmware, vocational education

1. Introduction

The rapid advancement of technology in the electronics industry demands a more modern, efficient, and safer approach in the production of Printed Circuit Boards (PCBs). PCBs are the backbone of almost every electronic device, serving as critical components that ensure functionality, reliability, and integration of circuits. The increasing demand for high-performance and sustainable PCBs has intensified the need for innovation in their fabrication processes (Ghelani 2024).

Conventional methods such as heat press techniques, chemical etching, and the use of materials like ferric chloride are still practiced in the electronics workshop of Vocational College Sungai Buloh. These approaches not only involve complex processes but also pose safety risks to students due to the use of hazardous chemicals, high consumable costs, and inconsistent circuit outputs that are prone to short circuits or open circuits (Misra et al., 2022). Studies also highlight that defects during PCB fabrication such as open circuits and short circuits are among the main causes of electronic system failures (Sankar & Sankar, 2022).

Moreover, concerns over environmental sustainability and the management of e-waste from discarded PCBs further emphasize the urgency of adopting greener and safer PCB production methods (Discarded e-waste/printed circuit boards: Springer, 2024). As such, there is a pressing need to design innovative PCB prototyping solutions that are not only cost-effective and efficient, but also safer for students and environmentally sustainable.

In response to these issues, an innovative system has been developed using open-source control technology based on Arduino Uno R3 and CNC Shield V3. This system controls the movement of motors along the X, Y, and Z axes via the GRBL platform and applies the milling process to replace chemical etching in the production of copper tracks. This innovation provides a safer, more cost-effective, environmentally friendly alternative that is well-suited for vocational education environments (Kumar et al., 2022). The mini CNC-based approach has also been proven effective in improving accuracy, reducing process time, and enabling students to understand real industrial technologies through project-based learning (Ingle & Raut, 2024).

Both developing and developed countries recognize the effectiveness of Arduino-based mini CNC machines in technical education. In India and Thailand, Megalingam et al. (2018) developed a CNC milling bot for engineering

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training, demonstrating its capability to efficiently produce PCB engravings. Rubani et al. (2024) proposed the development of user-friendly educational CNC systems suitable for basic engineering training. Meanwhile, in Germany and Australia, Arduino platforms are utilized in vocational education to teach G-code programming and fundamental industrial automation directly (Melendez, 2019). Furthermore, user safety has been emphasized, where Oke and Potgeiter (2024) highlight the importance of emergency stop buttons and automatic detection systems to protect users during the PCB cutting process.

However, significant gaps still exist in the use of available machines at the Vocational College Sungai Buloh workshop. Previously built in-house machines were found to have shortcomings in performance, safety, and material durability. They used mini hand drills that required manual control and lacked emergency stop buttons. Moreover, the use of wood as the machine frame increased the risk of damage due to moisture and fire. These deficiencies limited the machine's long-term use and negatively affected the overall student learning experience (Feng & Xiao et al., 2024).

Therefore, this study aims to develop a PCB printing machine prototype based on Arduino Uno R3 and CNC Shield V3 that is more efficient, safe, and modular. This innovation not only reduces reliance on conventional methods but also enhances students' technical skills with the latest industrial technologies. The study also addresses the knowledge gap in developing low-cost, small-scale educational CNC systems that are easy to operate and maintain by students and lecturers (Kumar et al., 2022; Ingle & Raut, 2024).

Accordingly, the objectives of this study are to design an efficient PCB printing machine that meets teaching requirements, develop the prototype machine using a combination of Arduino UNO R3, CNC Shield V3, motor drivers, and the HC-05 Bluetooth module, and test the functionality of the developed system in a real workshop environment to ensure its suitability for teaching and learning in the TVET context.

2. Methodology

This study applies the Waterfall design model as the methodological framework for developing a PCB printing machine using Arduino Uno R3 and CNC Shield V3. This model was chosen for its systematic and sequential structure, which allows each development phase to be implemented in an organized and focused manner. The five main phases of this model are: (i) requirements analysis, (ii) system design, (iii) development and implementation, (iv) testing, and (v) maintenance. As reference, refer Figure. 1.

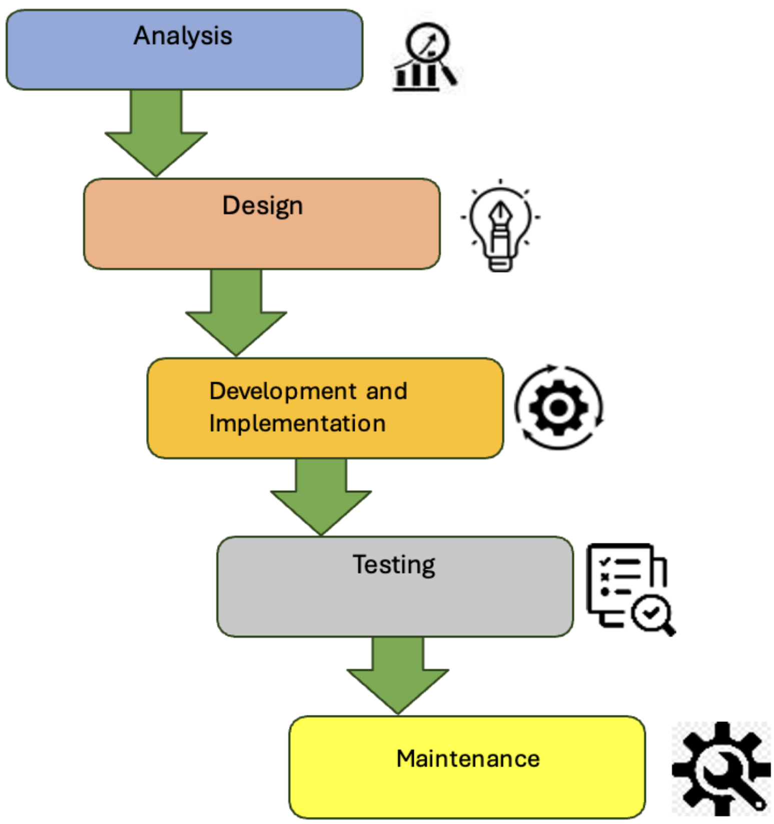

Figure 1: Waterfall Design Model

In the analysis phase, the system requirements were identified, including suitable electronic components and software. The main components consisted of the Arduino Uno R3, CNC Shield V3, NEMA 17 stepper motors, A4988 motor drivers, and a 775 DC motor as the spindle as presented in Figure 2. Software such as Fritzing, FlatCAM, and Universal Gcode Sender (UGS) was used for circuit design, G-code generation, and machine operation control.

Next, in the design phase, the researcher developed schematic diagrams of the electronic circuit wiring, the physical design of the machine casing, and the project program flowchart. System integration was managed to ensure that the mechanical and electronic components could function in harmony. The casing design was developed using PETG material for safety and durability purposes.

In the development and implementation phase, the researcher assembled all components according to the wiring diagram and programmed the GRBL firmware into the Arduino to control the stepper motors. PCB handling and production were carried out with G-code input from the user, transmitted through UGS to the CNC system. The system development also involved the integration of a Bluetooth module to enable remote control via smartphone.

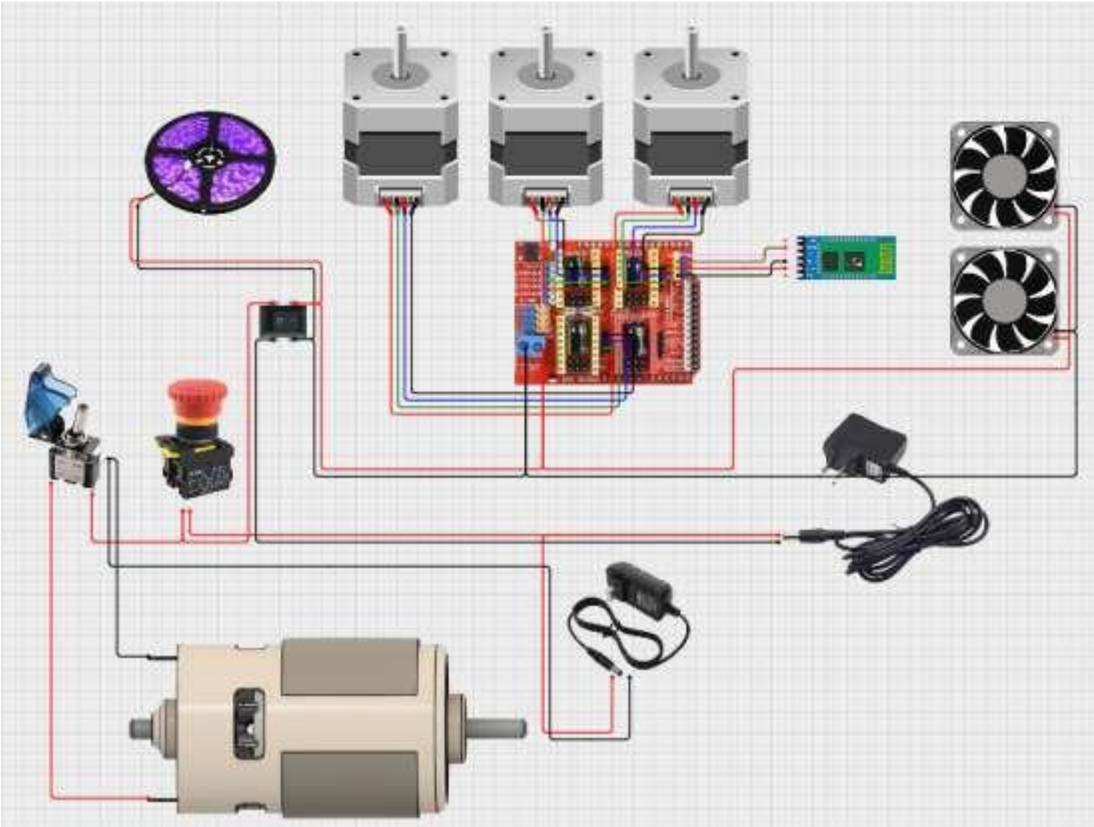

Figure 2: Project Wiring Circuit

2.2. Product Testing

Three main types of tests were conducted to evaluate the effectiveness and safety of the developed machine:

(i) Continuity test – using a multimeter to ensure all circuit connections were intact and no open circuits occurred;
(ii) Power supply voltage test – to ensure the voltage values at each connection point were stable and met the operational requirements of key components such as motors, switches, and controllers;
(iii) Functionality test – covering the testing of the power system, movement of the X-Y-Z stepper motor axes, spindle accuracy during the printing process, and the operation of the emergency stop button.

These three tests helped ensure that the developed PCB printing machine not only met technical requirements but also guaranteed safety during its use in a vocational education workshop. Any identified issues would be resolved through maintenance processes, such as connection adjustments, replacement of faulty components, and re-tuning of the system program as presented in Figure 3.

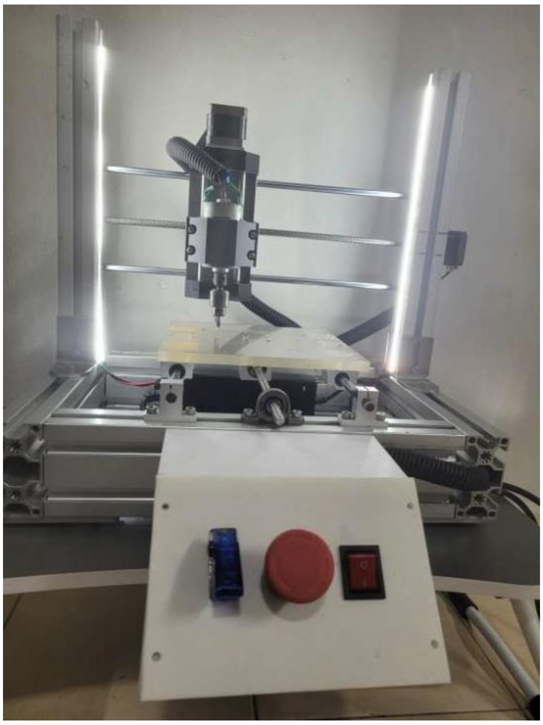

Figure 3: PCB Printing Machine

3. Research findings and discussion

3.1 Continuity and Voltage Testing

The results of the continuity test showed that the connections between the A4988 motor drivers and the stepper motors on all three axes (X, Y, and Z) were in good condition without any disruptions. Multimeter readings confirmed that all electrical connections were intact and stable, indicating that the motor control system functioned as designed. The voltage test also verified that the components received the appropriate power supply, with VMOT recorded at 11.9V (normal range: 8V–35V), while VDD was 4.9V (normal range: 3V–5.5V). These readings demonstrated that the overall system had sufficient power supply stability to operate smoothly.

3.2 Functionality Testing

During the functionality test, the machine system successfully activated all components including the stepper motors, cooling system, power switch, emergency stop button, and bluetooth module as presented in Table 1. The stepper motors on the X, Y, and Z axes were also successfully controlled using the UGS Platform 64 software. However, failures occurred during the initial PCB printing trials due to unsuitable calibration values and improper drill bit selection. As a result of the functionality tests conducted, it was found that the developed CNC PCB machine was able to perform its main tasks effectively after several improvements were made. In the initial test, the power system successfully activated all essential components such as the Arduino LED, cooling fan, Bluetooth module, as well as switches and motors. The effectiveness of the control system through UGS Platform 64 was also proven when all three stepper motors (X, Y, Z) operated smoothly, demonstrating that communication and GRBL firmware functions in Arduino worked as expected.

Nevertheless, critical issues were identified during the actual PCB printing phase, particularly concerning circuit path accuracy and engraving quality. The original calibration values (X=35, Y=35, Z=30) failed to produce accurate results, leading to unsuccessful PCB prints. This indicated that inaccurate calibration caused uneven paths, insufficient engraving depth, and incomplete cutting. The problem was resolved by adjusting the calibration values to X=40, Y=40, Z=30, which eventually produced more stable and precise results.

In addition, the type of drill bit used also influenced the printing outcomes. A 0.1 mm V-shape bit (10° angle) failed to produce clean and sharp engravings, often resulting in loss of copper tracks. In contrast, the use of a 0.1 mm tungsten carbide bit (60° angle) showed much better performance with consistent and accurate engraving results. This proved that the geometry and material of the cutting tool play a critical role in CNC-based PCB printing.

Table 1: Functionality Test Results

Component / Function Tested	Testing Method	Test Results	Remarks
Power system	Observation of LED lights and fan when the switch is turned on	All components active; Arduino LED lights up, fan operates	Power system stable and supply sufficient
Stepper Motor Movement (X, Y, Z)	Control via UGS Platform 64	All three axes move smoothly and respond to G-code commands	GRBL communication functions well
Bluetooth Module HC-05	Smartphone connection with UGS Bluetooth Controller	Connection successful; stable control at a distance of 2–3 meters	No delay in commands; remote control stable
Spindle Motor 775 DC	Observation of rotation when active	Rotates stably and responds well during engraving process	Smooth rotation, no vibration
Emergency Stop Button	Tested while the system is operating	System stops immediately when the button is pressed	Safety function works as designed
System Calibration (X, Y, Z)	Comparison of engraving results between original and new settings	Original values (X=35, Y=35, Z=30) failed; new values (X=40, Y=40, Z=30) accurate	Accurate calibration is crucial for circuit precision
Drill Bit Selection	Engraving using V-shape bit vs. tungsten carbide	V-shape bit failed; tungsten carbide 0.1mm (60°) produced cleaner and neater results	Drill bit type and angle greatly influence PCB engraving quality

More importantly, the emergency stop system tested demonstrated effectiveness by instantly shutting down the entire system during unexpected situations. This feature confirmed that user safety considerations were embedded in the prototype design, aligning with the project's primary objective to produce a system that not only functions well but is also safe for use in educational workshop environments.

The use of a 0.1 mm V-shape bit with a 10° angle failed to yield satisfactory printing results. Conversely, when a 0.1 mm tungsten carbide bit with a 60° angle was used together with calibration values of X=40, Y=40, and Z=30, the circuit was successfully printed neatly and accurately. This shows that precise calibration values and the correct tool selection play a decisive role in determining the quality of PCB printing.

3.3 Discussion

The development of the CNC PCB machine in this study demonstrates great potential as a practical technical solution in vocational education. The system's technical performance depends directly on the accuracy of system parameter settings and component selection, particularly calibration values and drill bit type. Findings showed that using a 0.1 mm tungsten carbide bit with a 60° angle, together with calibration values X=40, Y=40, and Z=30, produced clean and consistent PCB engravings. This aligns with the findings of Kumar et al. (2022), who emphasized the importance of engraving depth adjustment and proper tool selection to ensure PCB quality.

In terms of platform selection, the use of Arduino Uno and CNC Shield V3 demonstrated that open-source control systems are a cost-effective and flexible approach for technical training. Studies by Ingle & Raut (2024) support the effectiveness of GRBL systems in managing mini CNC operations for self-learning and practical experimentation.

In this project, the integration of the Bluetooth HC-05 module also expanded students' skills in automation and remote control, consistent with modern industrial demands. Practical tests showed that smartphone pairing with the HC-05 module took around 2–3 seconds within a ±3-meter range, enabling smooth and responsive control of movement commands (Khairul et al., 2022). This finding aligns with research at Politeknik Negeri Jakarta, which reported that the HC-05 module is suitable for CNC machine control applications in technical education.

In terms of motor performance, all three stepper motors were successfully operated smoothly across the X–Y–Z axes, and the DC spindle also performed steadily during engraving tests. This shows that micro stepping mode and current control via the A4988 drivers functioned effectively, supporting torque stability and consistent engraving depth. When controlled using the HC-05 module, no significant delays occurred in command processing, thus proving that the Arduino–GRBL platform can maintain motor performance even with wireless communication (Singh, Sahu, Beg, Khan, & Kumar, 2018).

User safety was also a priority in the prototype design. The emergency stop system tested functioned instantly during unexpected events, proving its effectiveness. This supports recommendations by Fortuna et al. (2024), who emphasized that educational CNC machines should be equipped with additional safety features to protect students in workshop environments.

Furthermore, the ability of students to adjust system parameters and select appropriate cutting tools reflects a problem-based design approach, which has proven effective in TVET contexts. Le (2024), in the context of developing countries, noted that integrating open-source technologies such as Arduino into CNC systems increases student access to low-cost practical training, thereby supporting learning through problem-solving.

This study also aligns with the principles of Project-Based Learning (PBL), widely applied in skills training. Students' active involvement in building, testing, and improving the system contributed to strengthening their technical competencies. This is supported by findings from Dahari et al. (2024) who stated that the use of technologies such as Arduino in TVET projects enhances students' technical understanding, creative thinking, and confidence in industrial technologies.

From a cost perspective, the prototype was developed at a total expenditure of RM853.01 (~USD180). Compared to modular mini CNC systems such as commercial educational-scale CNC machines priced between USD200 and USD2,000 (Kumar et al., 2022; Machay et al., 2024), this project's cost is significantly lower. Moreover, compared to basic DIY systems, which cost less than USD100 but lacked safety controls and modularity this prototype offers a balance between affordability, safety, and educational functionality. This demonstrates that the system is not only cost-effective but also suitable for widespread adoption in technical education institutions in developing countries.

Overall, this project not only proved its effectiveness from a technical perspective but also highlighted its educational innovation potential in empowering students through exposure to real industrial technologies, while supporting a Project-Based Learning (PBL) approach that has been shown to be effective internationally.

4. Conclusion

This study demonstrated that the development of a PCB printing machine based on Arduino Uno R3 and CNC Shield V3 can replace conventional chemical etching methods that are hazardous and costly. The prototype developed showed good performance in terms of electrical function, stability of the three-axis control system, and user safety through the integration of an emergency stop button. Adjustments to calibration values and the selection of cutting tools (tungsten carbide bit) played a critical role in ensuring neat and precise PCB engravings. Wireless communication via Bluetooth HC-05 also added flexibility and suitability for the TVET workshop environment.

Beyond technical aspects, this study contributes to vocational education pedagogy by incorporating an effective Project-Based Learning (PBL) approach. The development cost of only RM853.01 proved that educational innovation does not necessarily require high expenses, and open-source approaches such as Arduino and GRBL are practical and sustainable. Therefore, this project successfully achieved its main objectives and offers a technological solution model suitable for widespread use in TVET institutions in Malaysia and other developing countries.

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Conflict of Interest

The authors declare no conflicts of interest.

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