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IDC Innovation on Design and Culture

ISSN XXXX-XXXX
Volume 4, Issue 3
https://idc.iikii.com.sg
Innovation on Design and Culture

Article

A Modular Five-Axis CNC Educational Platform for Experiential Learning in Mechatronics

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Received: Jun 26, 2025; **Revised:** Jul 14, 2025; **Accepted:** Jul 29, 2025; **Published:** Sep, 30, 2025

Abstract: Recent advancements in electronic and information technology have propelled progress in smart manufacturing, IoT, and automated system architectures. However, the high cost and closed nature of conventional CNC systems continue to limit their accessibility in engineering education. This study addresses this challenge by developing a modular five-axis CNC educational platform based on the ESP32 microcontroller and open-source GRBL firmware. The system achieved ±0.1 mm repeatability, visualized five-axis synchronization, and enabled students to perform full CAD-to-machining workflows. This open and low-cost platform effectively bridges theoretical learning and hands-on practice, offering a scalable model for mechatronics education and demonstrating the application of intelligent control in modern manufacturing. Beyond its technical contribution, this work advances the democratization of engineering education and highlights the educational potential of experiential learning frameworks in modern mechatronics curricula.

Keywords: CNC, Mechatronics, Education, Smart Manufacturing, Vocational Education, Open-Source Hardware

1. Introduction

In recent years, the rapid evolution of electronics and information technology has become a major driving force behind the transformation of the manufacturing industry. The rise of smart manufacturing, artificial intelligence (AI), the Internet of Things (IoT), and automated system frameworks has reshaped the industrial landscape. According to Ryalat et al. (2024), the integration of mechatronics and Industry 4.0 is fundamentally reshaping manufacturing practices by enabling more intelligent, interconnected, and adaptive production systems. This transformation positions mechatronic integration as a central element in the construction of smart factories.

Building on this technological progression, Matin et al. (2023) emphasized that the convergence of AI and IoT, collectively referred to as AIoT, has become the foundation of sustainable smart manufacturing. Meanwhile, Chatzopoulos et al. (2024) demonstrated that open-source and low-cost mechatronic systems can serve as effective educational tools, fostering innovation through hands-on learning. Collectively, these studies highlight that the next stage of mechatronics education depends not only on intelligence but also on open, adaptable, and accessible platforms.

Despite advances in industrial technology and the trend toward efficiency and flexibility, traditional CNC machines remain difficult to adopt for small and medium-sized enterprises, educational institutions, and individual learners due to high costs, proprietary architectures, and maintenance complexity. The concept of *equipment as a pedagogical tool* is still underdeveloped in vocational engineering education, where instruction often relies heavily on simulation software. Although such software allows students to learn machining theory and G-code programming, it fails to provide opportunities to observe real-time axis motion, control feedback, and mechanical operation. As a result, students' learning often remains theoretical, limiting their understanding of integrated system architecture and hindering the accumulation of practical experience.

To address these issues, this study proposes a low-cost, modular five-axis CNC educational platform designed to lower the entry barrier and promote hands-on learning. The system employs readily available components, such as spindle and stepper motors, an open-source control framework, and command generation software to achieve high instructional value at minimal cost. The design process encompassed the development and fabrication of key structural elements, including the machine frame, gantry assembly, tool holder, and base platform. Precise geometric alignment was adopted as a fundamental principle to ensure motion accuracy and structural rigidity after assembly. Students performed an end-to-end workflow. Through this platform, vocational learners can disassemble, observe, and operate mechanical structures while exploring control-system logic and multi-axis coordination, thereby developing cross-disciplinary integration and problem-solving abilities.

1.1 System Framework

The proposed five-axis machining platform is designed primarily for hands-on student practice, using polyurethane foam blocks as the machining material to ensure safety and ease of observation during classroom activities. The workflow, illustrated in Fig. 1, consists of three major stages: (1) 3D modeling, where students design components using CAD software; (2) CAM toolpath generation, where the CNC code is automatically produced; and (3) CNC machining execution, in which the system performs cutting operations within the classroom environment.

This process enables learners to complete the full digital-to-physical fabrication cycle without the need for industrial facilities, allowing them to directly connect design concepts with machine operation.

In this framework, the machine adopts a three-linear (X/Y/Z) and dual-rotary (B/C) configuration, with both rotary axes mounted on the worktable side to enable multi-surface machining within a compact workspace (Dong et al., 2023). Similar to conventional five-axis CNC systems, the proposed model consists of three major subsystems: the mechanical system framework, the control system framework, and the software framework. Each functional module can be flexibly reconfigured according to instructional needs, enabling students to visually and practically comprehend how these subsystems interact within the overall control architecture.

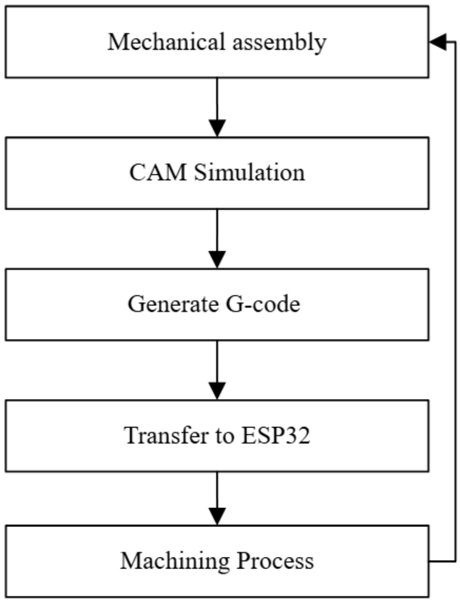

Fig 1. Workflow of the five-axis CNC machining process, showing the stages of CAD modeling, CAM toolpath generation, and classroom-based CNC machining using polyurethane foam materials. The system employs a three-linear (X/Y/Z) and dual-rotary (B/C) configuration for multi-surface machining (Authors' own work).

1.2 System Design and Component Selection

The design and manufacturing process began with 3D modeling to perform structural optimization and dynamic interference detection. After confirming feasibility, key components, including linear guide rails, lead screws, and the aluminum-extrusion frame, were assembled sequentially.

The main structure uses aluminum alloy, effectively reducing overall weight while maintaining sufficient rigidity and machining stability. Each of the five motion axes is independently driven by NEMA 17 stepper motors, enabling simultaneous multi-axis interpolation (Bernardi et al., 2022). The rotary B and C axes were fabricated through photopolymerization-based 3D printing using PETG material, chosen for its lightweight characteristics and modular design that facilitates disassembly, reassembly, and visual demonstration during classroom instruction (Baltić et al., 2024).

2. Materials and Methods

2.1 3D CAD Modeling and Designing

The mechanical components of the five-axis CNC teaching machine were designed and modeled using professional 3D CAD software. The design process encompassed the development and fabrication of key structural elements, including the machine frame, gantry assembly, tool holder, and base platform. Precise geometric alignment was adopted as a fundamental principle to ensure motion accuracy and structural rigidity after assembly.

During the design stage, critical modules were rapidly prototyped via 3D printing using PETG material to validate geometry, check motion clearance, and detect possible interferences. This iterative prototyping approach significantly shortened the development cycle from digital modeling to physical verification. The optimized configuration streamlined the assembly process, enhanced overall stiffness, and minimized mechanical backlash, thereby improving machining precision and stability.

2.2 Control System Design

The control architecture of the proposed system is based on an ESP32 microcontroller running open-source GRBL firmware (Hercog et al., 2023). The firmware was configured with a custom post-processor supporting five-axis coordinated motion across the X, Y, Z, B, and C axes. Communication between the ESP32 and the host computer was established via Wi-Fi, allowing the controller to receive and execute G-code commands for synchronized multi-axis operations.

Each motion axis was driven by a dedicated stepper motor and driver pair, while the ESP32 generated precise pulse signals through its GPIO outputs. Limit switches and an automatic homing routine were integrated to improve positioning accuracy and prevent overtravel or misalignment. The spindle system employed a 500 W brushless DC motor, providing stable cutting torque and adjustable rotational speed via PWM control.

2.3 G-code Generation

The machining toolpaths were generated using computer-aided manufacturing (CAM) software and exported in standard G-code format. These G-code files were transmitted to the ESP32 controller, where the firmware parsed linear (G1) and circular (G2/G3) interpolation commands and converted them into step signals for each axis.

Before machining, a homing procedure and work coordinate setup were performed to establish reference positions. The control interface, implemented through the Universal G-code Sender (eUGS) software (Das et al., 2024), provided real-time visualization and simulation capabilities. This allowed students to preview toolpaths, verify program integrity, and simulate motion before activating the spindle. Once the machining process commenced, motion commands were executed sequentially under the synchronized control of the ESP32. Upon completion, the system automatically returned all axes to their home positions, completing a closed-loop operational cycle.

This workflow enabled learners to observe the complete digital-to-physical transformation process, linking CAM-generated data to tangible multi-axis machining behavior.

2.4 Machine Assembly and System Integration

Following the fabrication of mechanical and electronic components, integration was carried out to merge the control system with the physical structure. During assembly, slide rails and lead screws were precisely aligned to maintain orthogonality and parallelism, as even minor deviations could reduce machining accuracy. Stepper motor mounts, spindle bearings, and couplings were verified for dimensional tolerances to ensure mechanical stability during operation.

Electrical wiring and firmware configuration followed the mechanical alignment process. Each axis was tested for directional consistency, signal mapping accuracy, and homing repeatability. After successful calibration, automated test cycles were conducted to evaluate repeatability and motion smoothness. Through iterative refinement, both hardware and software subsystems were tuned to operate cohesively, forming a stable and responsive five-axis educational platform.

The system verification and development followed a V-model approach (Fig. 2), which emphasizes iterative validation between design, implementation, and feedback stages (Wu, 2024). This model not only enhanced system reliability but also provided students with a clear framework for understanding the engineering design cycle used in professional CNC system development. The bidirectional feedback between the upper (conceptual design) and lower (validation and testing) phases helped illustrate how theoretical models translate into practical implementation, a valuable pedagogical process for vocational engineering education. This design-validation loop also mirrors the iterative design thinking processes commonly applied in product development education.

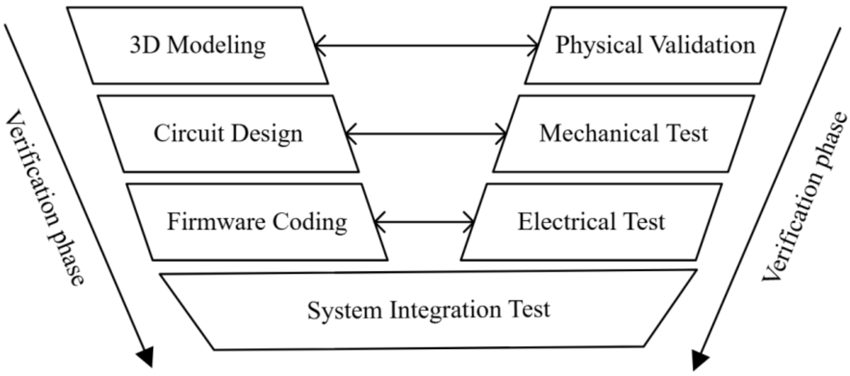

Fig 2. V-model framework for system development and verification, illustrating iterative validation between design, implementation, and feedback stages. The model emphasizes bidirectional connections between conceptual design, subsystem integration, and system testing, aligning with standard engineering development practices and supporting instructional demonstration of design–test feedback cycles (Authors' own work).

3. Results

3.1 System Architecture and Experimental Results

The modular five-axis CNC teaching prototype (Fig. 3) successfully achieved its intended goal of integrating mechatronic architecture into a compact, classroom-friendly educational platform. The assembled system measured approximately 380 × 300 × 320 mm, providing a structurally stable yet portable design suitable for instructional environments. Machining verification experiments conducted with polyurethane foam and polymer composite materials demonstrated a repeat positioning accuracy of ±0.1 mm, meeting the pedagogical precision requirements for vocational and engineering education.

Students performed an end-to-end workflow, from 3D CAD modeling and G-code generation to physical machining, using the ESP32-based GRBL control framework. Real-time visualization through the Universal G-code Sender (eUGS) interface enabled learners to monitor toolpath execution, spindle response, and multi-axis motion synchronization. This interactive control environment effectively connected digital design to tangible machining processes, reinforcing students' comprehension of the data-to-motion transformation within mechatronic systems.

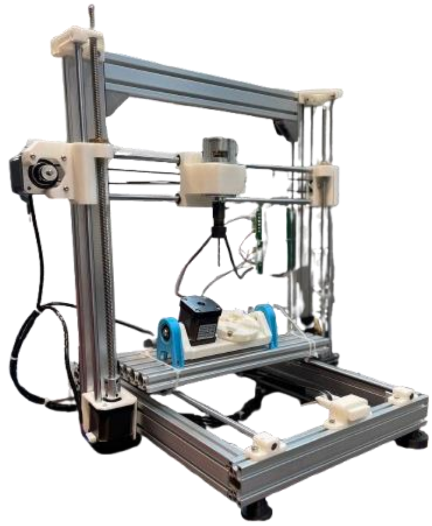

Fig 3. Modular five-axis CNC teaching prototype designed for classroom demonstration, featuring a compact aluminum-extrusion frame and transparent PETG rotary modules. The system demonstrates five-axis synchronized motion (X/Y/Z linear and B/C rotary) under the ESP32 + GRBL control framework. This visual and modular configuration allows students to observe kinematic relationships and feedback behavior during machining, reinforcing experiential and inquiry-based learning in vocational mechatronics education (Authors' own work).

3.2 Teaching Observation and Learning Outcomes

Observation during laboratory sessions revealed heightened student engagement, collaboration, and problem-solving initiative, particularly when using the transparent PETG rotary module. The visual exposure of the B/C-axis rotation enabled students to observe multi-axis interpolation, motion feedback, and mechanical coupling effects in real time. Such direct observation deepened their understanding of kinematics and control synchronization, supporting inquiry-based learning and experiential comprehension of system dynamics (Fig. 4).

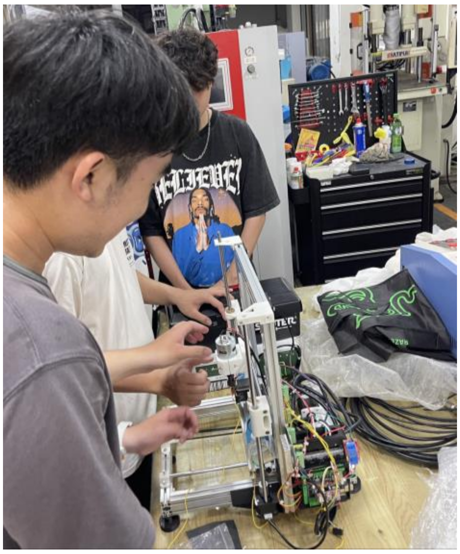

Fig. 4. Students interacting with the modular five-axis CNC teaching platform during a laboratory session. The hands-on practice allowed them to observe real-time motion coordination and test G-code execution under instructor supervision, enhancing engagement and comprehension of mechatronic system behavior.

To further evaluate the platform's instructional effectiveness, we conducted a post-activity survey among 20 vocational students. Participants rated their learning experiences across four key dimensions using a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree): multi-axis motion comprehension, control system logic, interdisciplinary integration, and problem-solving confidence. The proportion of students selecting "Agree" or "Strongly Agree" and their corresponding average scores are summarized (Table 1). Beyond the numbers, students' written feedback clearly showed the learning benefits of the platform. Many mentioned that by operating the transparent rotary modules, they could actually see how digital commands turned into real mechanical movement, which helped them understand how coding and motion are connected. Some students said the modular design made it easier to try different settings and discuss problems with classmates, which improved teamwork and confidence. Teachers also found that the open-source design and visible moving parts made demonstrations easier to explain and more engaging for students.

The assessment results indicate high levels of student satisfaction and learning effectiveness improvement, particularly in multi-axis motion comprehension and control system logic.

Table 1. Summary of student feedback on the five-axis CNC teaching platform.

Learning Dimension	Mean Score (1–5)	Agreement (%)	Representative Feedback (Qualitative)
Understanding of multi-axis motion	4.6	85%	Students could clearly observe the coordinated motion of the B/C axes.
Control-system logic	4.5	82%	The ESP32 interface was intuitive and easy to use for code testing.
Interdisciplinary integration	4.3	80%	The platform effectively combined mechanical concepts with programming practice.
Problem-solving confidence	4.4	84%	Students found it easier to debug and analyze motion-related issues.

Survey results indicate that over 85% of participants agreed or strongly agreed that the platform enhanced their conceptual understanding and practical engagement. These findings align with classroom observations, confirming the system's effectiveness in supporting experiential and inquiry-based learning within mechatronics education.

Overall, these results confirm the platform's effectiveness as a low-cost, open-source CNC training system that bridges theoretical learning with practical application. The modularity and visual accessibility of its components make it a valuable tool for developing interdisciplinary competencies in mechatronics education, promoting experiential and inquiry-based learning in line with contemporary smart-manufacturing pedagogy. In a pilot classroom implementation, more than 85% of participating students reported improved understanding of multi-axis motion control and mechatronic system integration, indicating the platform's positive impact on learning outcomes.

4. Discussion

The proposed five-axis CNC teaching system illustrates how the integration of open-source control and modular mechanical design can effectively enhance mechatronics education. In contrast to traditional industrial CNC machines, which are often inaccessible due to high costs, safety restrictions, and maintenance complexity, this lightweight educational platform enables students to directly observe and manipulate control logic, motion synchronization, and feedback mechanisms within a safe and interactive classroom environment.

As summarized in Table 2, the adoption of open-source frameworks and modular architecture not only reduces cost but also enhances scalability for future development. In practical educational settings, the ESP32 controller provides a flexible foundation for system expansion, including the integration of human–machine interfaces (HMI)**,** sensor-based data logging, and AI-enabled process monitoring. These extendable features align with current pedagogical trends that emphasize reconfigurable, adaptive learning tools capable of evolving alongside technological progress in smart manufacturing (Neves & Ribeiro, 2024). Furthermore, this educational approach reflects the principles of maker education and constructivist learning, where students actively engage in creative problem-solving and collaborative exploration through tangible design practices.

Table 2. Key advantages of the proposed five-axis CNC teaching system.

Category	Main Advantages
Low Cost and Open Source	Utilizes the ESP32 microcontroller with GRBL open-source firmware and 3D-printed components, significantly reducing overall cost while maintaining flexibility for hardware and software customization.
Compact and Portable	Employs a lightweight aluminum-extrusion frame (380 × 300 × 320 mm), ensuring structural stability while allowing convenient relocation and classroom deployment.
Modular and Visual Design	Features disassemblable components and transparent PETG rotary modules that enable direct visual observation of mechanical motion, facilitating hands-on learning and maintenance training.
High Educational Value	Demonstrates genuine five-axis coordinated motion and integrated control, effectively bridging theoretical instruction with practical experience in mechatronics education.
Scalable for Future Development	Supports future extensions such as HMI integration, sensor-based monitoring, and data-driven analytics for smart-manufacturing and AI-assisted teaching applications.

The transparent and modular configuration of the platform further encourages collaborative experimentation among students. Instructors can design customized exercises focusing on specific dimensions of control theory, kinematic relationships, or software optimization. Its portability and reconfigurability also support blended and remote learning environments, which have become increasingly important in engineering education in the post-pandemic era.

Overall, these findings highlight that low-cost, open, and scalable educational platforms can act as catalysts for transforming vocational mechatronics training. By simulating authentic industrial workflows, they foster inquiry-based learning and experiential problem-solving, bridging the gap between digital design, mechanical execution, and cognitive understanding. The proposed approach thus represents not only a technological contribution but also a pedagogical innovation that aligns with the evolving culture of smart-manufacturing education. Furthermore, this approach reflects a broader cultural shift toward open and collaborative design practices in engineering education.

5. Conclusions

This study developed a modular five-axis CNC teaching system based on the ESP32 microcontroller to lower the entry barrier for mechatronics education. Through systematic design, fabrication, and validation, the platform demonstrated stable mechanical performance, a repeat positioning accuracy of ±0.1 mm, and effective translation of simulated G-code data into physical machining operations.

By combining open-source GRBL firmware, 3D-printed rotary modules, and an aluminum-extrusion frame, the system achieved a balance between cost efficiency, instructional safety, and visual interactivity. It effectively bridged theoretical learning and hands-on practice, enabling students to acquire interdisciplinary competencies and develop problem-solving skills through authentic mechatronic integration.

Future research will focus on integrating smart-manufacturing features, such as human–machine interface (HMI) dashboards, sensor-based feedback, and cloud-enabled data analytics, to align the platform with emerging intelligent production systems. Beyond its technical contributions, this work embodies the principles of openness, accessibility, and educational democratization, reflecting a broader cultural transformation toward open and collaborative design practices in modern engineering education. This approach can be further integrated into smart-manufacturing curricula to foster sustainable learning ecosystems.

Author Contributions: Conceptualization, C.-W. Hsu and J.-H. Cheng; methodology, C.-W. Hsu; investigation, C.-W. Hsu; data curation, C.-W. Hsu; writing, original draft preparation, C.-W. Hsu; writing, review, editing, and supervision, J.-H. Cheng. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Technology Council (NSTC), Taiwan, under Grant No. NSTC 114-2813-C-992-030-H.

Data Availability Statement: The data of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors acknowledge the strong support of the Product Integration Design and Pilot Production R&D Center and the Intelligent Manufacturing and Smart Materials Research Service Center at the National Kaohsiung University of Science and Technology, which provided comprehensive facilities for product design, machining, assembly, and experimental validation throughout this study.

Conflicts of Interest: The authors declare no conflict of interest.
in the main text. In the appendixes, Figures, Tables, *etc.* should be labeled starting with 'A', e.g., Figure A1, Figure A2, *etc.*

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