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USB Breakout-Controlled Modular CNC System for Affordable Smart Manufacturing Solutions

Budi Artono^{1,*}, Basuki Winarno², Hendrik Kusbandono³, Frian Adi Anata⁴,
Shashi Kant Gupta⁵

¹Electronics Engineering Technology, State Polytechnic of Madiun, Madiun, Indonesia

^{2,4}Electrical Engineering, State Polytechnic of Madiun, Madiun, Indonesia

³Information Technology, State Polytechnic of Madiun, Madiun, Indonesia

⁵Ph.D. & Researcher, CSE, Integral University, Lucknow, UP, India

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Correspondence:

E-mail: budiartono@pnm.ac.id

ABSTRACT

The primary objective of this study is to design, develop, and experimentally validate a low-cost modular CNC system controlled via a USB Breakout Controller as an affordable machining solution for small-scale wood manufacturing. The research employed an experimental approach involving the fabrication of an 18 mm plywood test specimen under three feed-rate settings (40%, 50%, and 70%) to evaluate dimensional accuracy, machining time, and surface quality. The CNC prototype was constructed using stepper-driven linear axes, a 500 W spindle, and Mach3-based motion control. Validation procedures included repeated measurements of machined features using a ruler, surface quality inspection, and comparison of actual versus nominal dimensions. The results demonstrate that the system achieved dimensional deviations between 0.32 mm and 0.58 mm across trials, with the optimal performance observed at a 50% feed rate, which produced the lowest mean error (0.32 mm), smoothest surface finish, and efficient machining time (54 seconds). These quantitative findings confirm that the proposed system delivers machining accuracy comparable to entry-level commercial CNC routers while significantly reducing system complexity and cost. The study's novelty lies in demonstrating the effectiveness of a USB-based modular controller architecture for precision wood machining—an area where low-cost systems typically suffer from poor stability and inconsistent performance. This research concludes that the developed CNC system is technically viable, repeatable, and suitable for vocational education and small-to-medium wood fabrication industries requiring affordable digital manufacturing solutions.

1. INTRODUCTION

The accelerated progress of the Industrial Revolution 4.0 has reshaped the landscape of science, engineering, and manufacturing by shifting production systems from manual labor to automation driven by robotics and sensor-based technologies (Jamwal et al., 2021; Rahaman et al., 2025; Kumar et al., 2025). In this evolution, Computer Numerical Control (CNC) machining has become a fundamental component of modern manufacturing due to its capability to deliver high precision, repeatability, and process efficiency (Yao K.-C et al., 2024; Xusheng Lin et al., 2025; Dhouib, 2023). CNC plotters further exemplify these advantages by enabling accurate translation of CAD/CAM outputs into two-dimensional or three-dimensional machining paths using standardized G-code instructions (Ramiz et al., 2025; Utpal Chandra Das et al., 2024).

Despite the maturity of CNC technology, adoption remains limited in many educational institutions and small-scale manufacturing sectors because commercially available systems often require high investment costs and involve complex operational integration. This challenge has driven the development of various low-cost CNC solutions; however, these alternatives commonly exhibit technical

constraints such as limited structural rigidity, unstable motion control, inconsistent dimensional accuracy, and inadequate surface finish quality. In addition, automatic setup and tuning—critical factors for performance optimization—are generally underdeveloped in low-cost systems (Guo C.H. et al., 2019). Recent studies on compact CNC technologies highlight ongoing improvements in flexibility, efficiency, and energy-saving capabilities (Jiejun Xie et al., 2025; Liping Wang et al., 2024), yet their effectiveness still varies significantly depending on controller architecture and motion system design.

These limitations are particularly evident in the speaker box fabrication industry, where many workshops continue to rely on manual cutting processes. Such manual operations often result in dimensional inaccuracies, non-uniform surface quality, longer machining times, and inconsistent productivity. Consequently, there is a pressing need for an affordable CNC solution that offers greater precision, stable machining performance, and adaptability for wood-based manufacturing tasks. Technology roadmapping frameworks further emphasize the importance of aligning system design with industry needs, identifying technological gaps, and supporting product development for future manufacturing requirements (Watanabe, 2022; El-Warrak, 2022; Miao, 2022). Within this context, low-cost CNC platforms have been highlighted as potential enablers for improving accessibility to automation in both industry and education (Jayabhaduri Radhakrishnan et al., 2025).

However, a clear research gap remains: although low-cost CNC prototypes are increasingly available, there is insufficient empirical validation regarding the performance and feasibility of CNC systems that utilize a USB Breakout Controller as the primary control interface. Specifically, the stability of motion control, dimensional accuracy, and surface finish produced by USB-controlled CNC systems for wood machining—particularly for speaker box production—has not been comprehensively assessed. Likewise, their suitability as instructional tools for vocational and technical education has not been thoroughly explored.

To address this gap, this research develops a low-cost, modular 3-axis CNC system integrated with a USB Breakout Controller and evaluates its machining performance through experimental testing. The study investigates dimensional accuracy, machining time, and surface quality when processing 18 mm plywood under different feed-rate settings (40%, 50%, and 70%).

The significance of this study lies in its contributions to both manufacturing practice and educational development. For small-scale wood fabrication industries, particularly in speaker box production, the proposed system offers a cost-effective alternative capable of improving accuracy and operational consistency. For vocational and technical institutions, the modular and USB-based architecture provides an accessible platform for teaching CNC programming, CAD/CAM workflows, and digital manufacturing processes, thereby supporting broader adoption of Industry 4.0 competencies.

2. RESEARCH METHODS

The research methodology was structured to ensure that the development, configuration, and performance evaluation of the USB Breakout Controller-based CNC system were conducted systematically and reproducibly. The methodological stages follow the research flowchart (Figure 1), consisting of data collection, hardware design, software configuration, system integration, calibration, and machining performance testing.

The research procedure follows the workflow illustrated in the flowchart (Figure 1). The process begins with the creation of the machining model, which includes CAD design, CAM toolpath generation, and conversion into G-code. The resulting machining instructions are then imported into Mach3 for execution. The next stage involves setting up the workpiece and preparing the cutting tools according to the material specifications. Once the mechanical setup is complete, the CNC machine undergoes a calibration process, including axis referencing and a dry run to ensure that the programmed toolpath aligns with the intended cutting trajectory.

After successful calibration, the machining operation is initiated. During this stage, the spindle speed, feed rate, and axis movements are continuously monitored to detect abnormalities such as tool chatter, missed steps, or unexpected vibration. Upon completion of machining, the workpiece is inspected to evaluate dimensional accuracy, surface quality, and overall conformity with the design specifications. If deviations are detected, the program or tool configuration is adjusted, and additional machining passes or corrective operations are performed. If no adjustments are required, the finished part is removed, and the process concludes. This iterative structure ensures that both the CNC system and the machining parameters are validated through repeated verification and refinement.

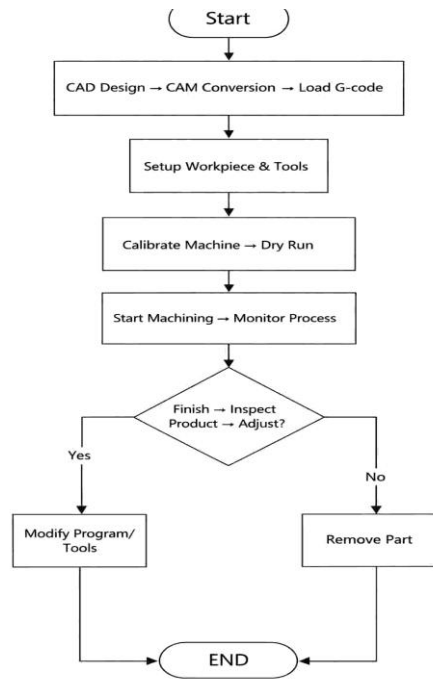


Figure 1. Research flow chart

2.1. Data Collection

Initial data were collected through direct observation of the prototype CNC system, focusing on structural rigidity, spindle behavior, stepper motor response, and motion stability. This stage identified mechanical and electrical limitations that informed the subsequent design and optimization steps. Additional data were gathered from manufacturer specifications for stepper motors, linear rails, spindle units, and Mach3 configuration guidelines.

2.2. Hardware Design

The hardware design of the CNC prototype consists of four primary components: the USB Breakout Controller, spindle unit, linear rail system, and stepper motor assembly. Each component is selected and integrated to ensure stable motion control, structural precision, and compatibility with Mach3-based CNC operation. The design emphasizes reproducibility, modularity, and electrical–mechanical reliability to support wood machining applications.

2.2.1. USB Breakout Controller

The USB Breakout Controller (Figure 2) functions as the main interface between the computer and the CNC motion system. It converts digital control signals generated by Mach3 into step-and-direction commands required by the motor drivers. The controller also manages peripheral I/O operations, including limit switches, spindle activation, and emergency-stop input. The module communicates through USB and operates similarly to a parallel-port controller, enabling integration with: Stepper motor drivers and Spindle control output.



Figure 2. USB Breakout Controller

2.3. Trimmer Spindle

The spindle serves as the beating heart of the CNC machine - not just housing the cutter, but precisely controlling its rotation and Z-axis movement. Powered by a motor through belt transmission or coupling systems, this vital component directly interacts with workpieces, making it the most critical

contact point in machining operations. For this CNC design, we've selected a Spindle Motor + ER11 Collet combination capable of 3,000-12,000 RPM speeds with 500W power output (shown in Figure 3).

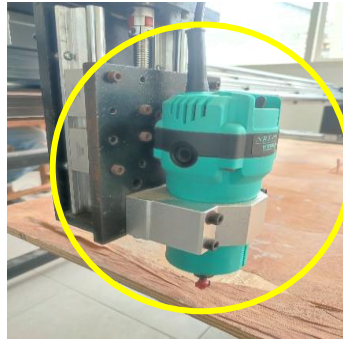


Figure 3. Trimmer Spindle

2.4. Linear Rail

Linear rails are precision-engineered guide systems that enable smooth sliding or rolling motion along a straight path. Constructed from high-strength galvanized and hardened steel, these corrosion-resistant components utilize advanced rolling technology for exceptional accuracy in linear motion applications. As shown in Figure 4, a complete linear guidance system consists of: Guide Elements: Linear rails, Linear bushings, Ball screws, Cross roller guides, Slide rails. Drive Mechanisms: Ball screws, Belts, Hydraulic/pneumatic systems, Linear motors. These systems form the backbone of precision motion control in modern machinery, ensuring repeatable linear movement with minimal friction.



Figure 4. Linear Rail

2.5. Stepper motors

Stepper motors (bipolar/unipolar) provide precise angular movement in fixed steps (0.75° – 1.8° per pulse). By controlling pulse timing, they achieve accurate positioning and directional rotation—smaller steps yield higher precision. (K. S. Win et al., 2023) (Figure 5).



Figure 5. Stepper motors

2.6. Software Design

2.6.1. SolidWorks

SolidWorks is a CAD (Computer-Aided Design) software developed by Dassault Systèmes. It is widely used by engineers, designers, and manufacturers to create precise 3D models, simulations, analyses, and technical drawings.

2.6.2. Mach3 Controller

MACH3 is a CNC machine control software that translates programs (such as G-code) into machine tool motion commands. Compatible with Windows 2000/XP/32-bit Vista, this software sends signals to the driver via the PC's parallel port—or through a USB/ethernet motion controller if a parallel port is unavailable. Flexible for various CNC machines (milling, lathe, plasma cutter, router), MACH3 supports up to 6 axes of simultaneous motion, including circular (2-axis) and linear interpolation. Its strength lies in its ability to generate precise step and direction pulses, making it an efficient solution for industrial automation. (Figure 6).

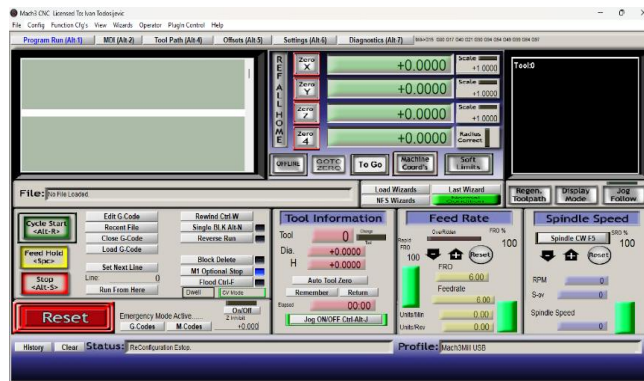


Figure 6. Mach3 Controller

2.7. Device Schematic

Refer to Figure 7, which illustrates the device schematic showing the power flow from an AC source to a circuit breaker (MCB) and then to the power supply. The system includes four stepper motors—labeled stepper motor x, y, and z—each independently controlled by four dedicated motor driver modules. Acting as the control hub, the USB Breakout Controller generates precise command signals to regulate the stepper motors' motion. The diagram highlights an intricate network seamlessly integrating the power supply, USB Breakout Controller, motor drivers, and stepper motors into a cohesive system.

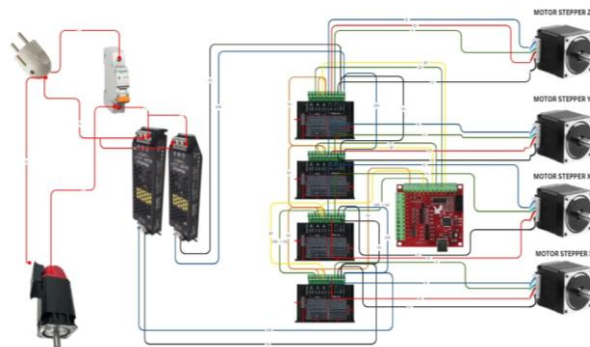


Figure 7. Device schematic

The CNC represents a modern industrial revolution - an advanced Computer Numerical Control (CNC) machine capable of precision cutting, detailed engraving, and material shaping with micron-level accuracy. This versatile system can process various materials including wood, acrylic, soft metals, and composites, automatically guiding its cutting tools based on programmed digital designs. Every movement is controlled with microscopic precision, enabling consistent, repeatable production of high-quality workpieces. Figure 8 provides a complete visual reference of the CNC design configuration.

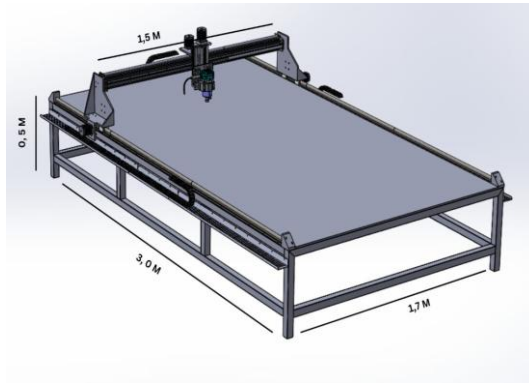


Figure 8. CNC design

3. RESULT AND DISCUSSION

To ensure optimal performance of all components and obtain accurate data, conduct a comprehensive analysis using the following steps. Subsequently, perform thorough testing of each device and the entire workflow system - from input to output - to verify functionality while analyzing the resulting data.

3.1. CNC machine's physical

The physical realization of the USB Breakout Controller-driven CNC system follows a three-phase assembly methodology: structural framework fabrication, linear motion component integration, and control signal wiring interconnection (Figure 9).



Figure 9. CNC machine's physical

3.2. CNC control panel

The machine's control panel is crafted from durable steel plate, featuring a compact design measuring 30 cm (length) × 20 cm (width) × 40 cm (height). Its robust yet functional build is illustrated in Figure 10.

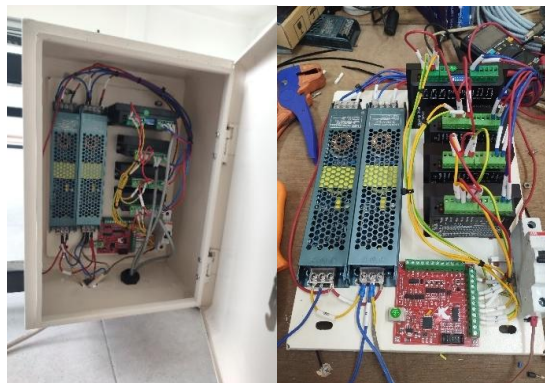


Figure 10. CNC control panel

3.3. Mach3 Calibration as a CNC Software Interface

The calibration process for the CNC machine’s movement is essential to ensure alignment between motion commands issued via the computer interface and the machine’s actual execution. For instance, when a displacement command of 100 mm along the X-axis is programmed, the machine must move precisely 100 mm without deviation. Accurate calibration is a critical prerequisite to guarantee the CNC machine’s operational precision. The calibration procedure can be performed through the following key steps: Initialize Mach3 Interface, Open the Mach3 application, then select the “Settings Alt6” menu to access the configuration panel (Figure 11).

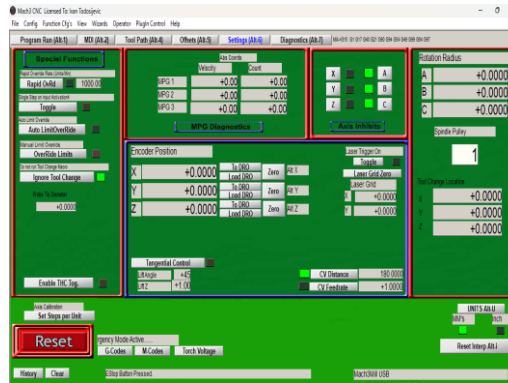


Figure 11. Mach3 alt6

Access Calibration Menu, In the settings panel, click “Axis Calibration” to begin the calibration process. Select Axis to Calibrate, The CNC machine has three primary axes (X, Y, and Z), each calibratable separately. For this guide, we will calibrate the X-axis by selecting X Axis in the calibration menu. Input Axis Movement Value, Enter the desired movement value (e.g., 50 mm), then click OK. Important Note: Before confirming, mark the initial position of the X-axis as a reference. After clicking OK, the X-axis will move according to the entered value. Measure and Validate Movement, Measure the actual distance moved by the X-axis using a precision tool (in millimeters). Input the measured result into the Mach3 calibration menu and confirm by pressing OK. Confirm Calibration Results, If the calibration is accurate, select YES to save the settings. If discrepancies exist, choose NO and repeat the calibration process from step (c). Calibrate Y and Z Axes, Repeat the same steps to calibrate the Y and Z axes, ensuring precise movement across all machine axes.

The experimental/technical process was carried out as follows: Plugin Configuration Verification, Access the plugin configuration menu and ensure that PluginConfig has been properly integrated. Verify that the seeNVUM_SK option is correctly configured, as shown in Figure 12. Motor Operating Parameters, To configure the motor parameters, navigate to the ‘Motor Settings’ submenu under the ‘Config’ menu, then refer to Figure 13. for the motor parameter configuration dialog.

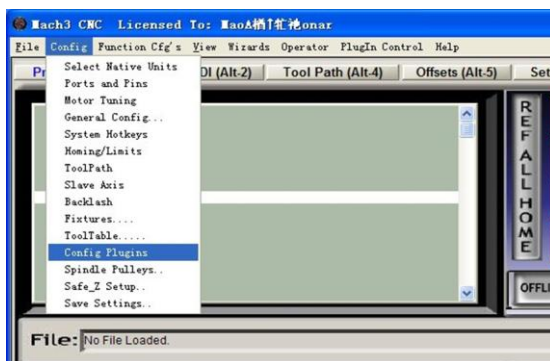


Figure 12. Plugin Configuration Verification

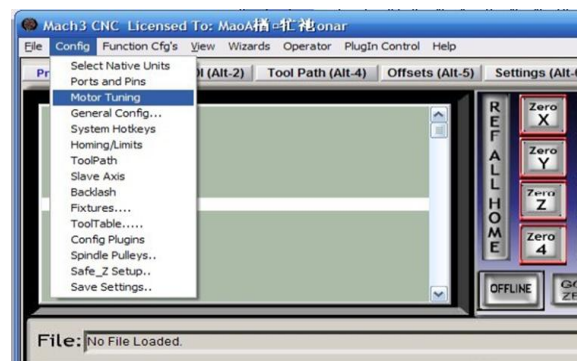


Figure 13. Motor Operating Parameters

The motor operational parameters are defined as follows: Steps per Pulse, Each step per pulse corresponds to the number of pulses required to achieve 1 mm of axial movement. This value is determined by the lead screw pitch and the motor driver segment configuration. For example, in a system with a 2.5 mm pitch and a 2-phase, 8-segment motor, the calculation is: $\text{Steps per Pulse} = (8 \times 200) / 2.5 = 640$. Speed Setting, The axial speed is set in mm/s. The standard and recommended value is 1500 mm/s. Acceleration, Acceleration is expressed in mm/s², with an optimal value of 200 mm/s². Step Pulse Width, The step pulse duration is set with a default width of 2.5 μs. Direction Pulse, The direction pulse also uses a default width of 2.5 μs.

Port Settings, Port Settings can be configured by opening the "Port and Pin" submenu (Figure 14) and selecting the "Configuration" option in the Port settings dialog box. Within this subpage, the following settings are available: Motor Output – Adjusts output parameters for motor control. Input Signal – Configures input signals from external devices. Output Signal – Modifies output signals for actuators or peripherals. Spindle Settings – Optimizes operational parameters for the spindle. To begin, first click "Motor Output" to define the basic system configuration.

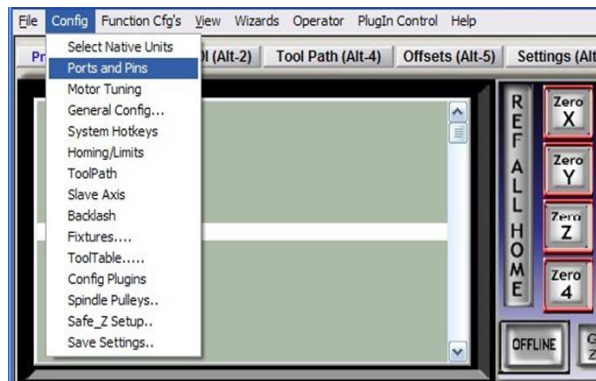


Figure 14. Port Settings

On this page, users can select stepper motor control through the provided menu without manually specifying pins. After selecting a menu, navigate to 'Input Signal' to access the input signal settings page, where configurations can be adjusted according to actual needs. Optional features include: Upper and lower limits for 6 axes (XYZABC), HOME position for 6 axes (XYZABC), PROBE settings, including ESTOP configuration (with default probe pin number 2 and ESTOP pin number 1). Additionally, users can switch to 'Spindle Settings' to configure spindle parameters as required.

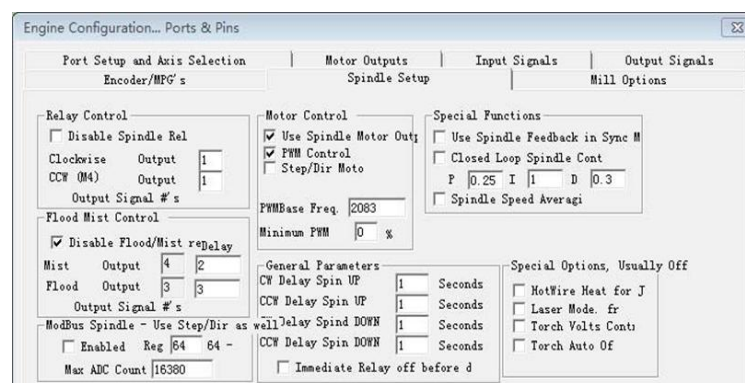


Figure 15. Spindle Settings

Next, the spindle was configured with Clockwise (CW) rotation, Reverse Counterclockwise (CCW), Mist, and Flood settings (Figure 15). These parameters were assigned values 1, 2, 3, and 4, corresponding to Output#1~Output#4. Within the output signal settings dialog, Output#1~Output#6 can be mapped to four primary control signals, including M3, M7, and M8 in the G-code. Specifically, the CW signal is controlled by OUT1, MIST by OUT2, and Flood by OUT3. For spindle speed control via Pulse Width Modulation (PWM), users may enable the "Use Spindle Motor Output" option and select "PWM Control". The PWM pin is preset to a dedicated default pin, eliminating the need for additional configuration.

4. STEPPER MOTOR TESTING

The stepper motor's performance was evaluated through a structured testing protocol, as detailed in Table 1. The experimental sequence commenced with static tests (no input pulse) on the CNC machine, proceeded to dynamic tests under applied pulse commands, and measured the corresponding mechanical response." The X-axis testing procedure began with a calibration process by defining its zero reference point using the "Zero X" command in the Mach3 CNC control software, which transmits the required pulse signals to the stepper motor driver. In the initial stage of testing, the system's baseline condition was observed without applying any input pulse. The steady-state response of the X-axis under this control condition is shown in Figure 16, while the physical condition of the X-axis prior to the application of the pulse signal on the CNC machine is presented in Figure 17. The position and vibration data obtained from

this steady-state condition were used as baseline data for comparison with the system's dynamic response.

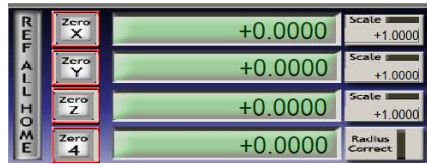


Figure 16. The X-axis in its steady state before the application of a pulse signal

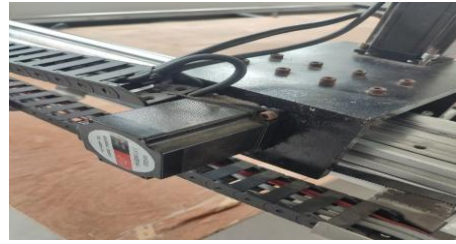


Figure 17. The X-axis in a stable state prior to the application of a pulse signal on the CNC machine.

Subsequently, a pulse signal was applied through the CNC software, generating a dynamic response in the X-axis and resulting in a positional displacement of 5 mm. The software display of the X-axis following the application of the pulse signal is shown in Figure 18, while the physical position of the X-axis after receiving the pulse input command via the CNC controller is illustrated in Figure 19. These results demonstrate a clear distinction between the steady-state condition before pulse application and the dynamic condition after the pulse signal was introduced, confirming that the system responded accurately to the input command.

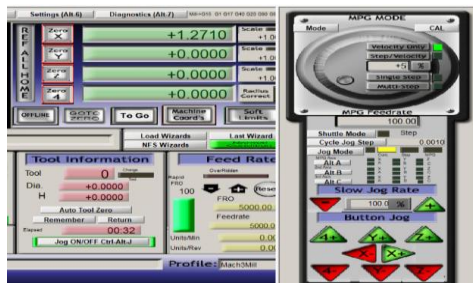


Figure 18. The X-axis following the application of the pulse signal.



Figure 19. Position of the X-axis after receiving a pulse input command via the CNC controller.

5. PRODUCTION VALIDATION TESTING

This process as detailed in Table 2, constitutes a production test on the CNC machine, designed to evaluate its performance based on various design drawings and operating system parameters. The subsequent section details the applied variations and machine configurations. The testing was conducted using an 18 mm thick plywood medium, cut into a rectangular blank.

The cutting performance of the CNC machine was evaluated by varying the feed rate parameter in the Mach3 software to 40%, 50%, and 70% of its programmed value. When the feed rate was set to 40%, the plywood cutting results produced dimensions that were consistent with the design specifications; however, the surface quality was suboptimal. The cut surface exhibited relatively high roughness and noticeable wood fiber tear-out, as illustrated in Figure 20.

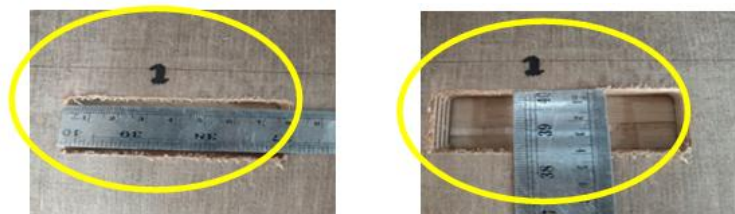


Figure 20. Cutting Result at a 40% Feed Rate.

When the feed rate was increased to 50%, the cutting process demonstrated improved performance. The machining time was more optimal while maintaining high dimensional accuracy in accordance with the design requirements. In addition, the surface finish showed better smoothness, characterized by lower surface roughness and a cleaner edge profile, as shown in Figure 21.

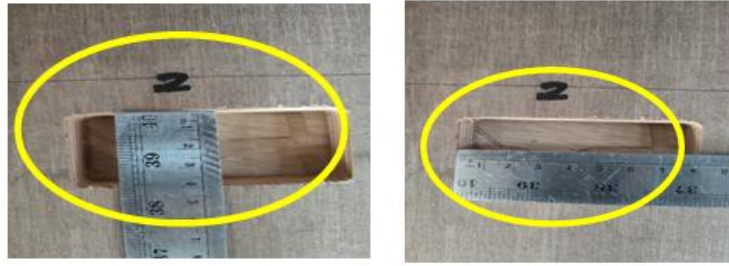


Figure 21. Cutting Result at a 50% Feed Rate.

At a 70% feed rate setting, the CNC machining process produced components with high dimensional accuracy and an even smoother surface finish, making this parameter suitable for applications where surface quality is critical. However, this improvement in finish quality was accompanied by reduced machining efficiency due to a longer processing time. The cutting results at this feed rate are presented in Figure 22.



Figure 22. Cutting Result at a 70% Feed Rate.

Based on Table 3, the results indicate that a 50% feed rate produces the lowest dimensional deviation (0.32 mm) and thus the highest accuracy, whereas both lower (40%) and higher (70%) feed rates increase deviation due to prolonged tool–material contact causing friction and fiber tear-out at the lower setting and vibration from higher dynamic loading at the upper setting, collectively demonstrating that moderate feed rates yield optimal tool loading and motion stability in accordance with CNC machining principles.

Table 3. Accuracy Across Feed-Rate Settings

Feed Rate	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)	Mean Error (mm)
40%	0.58	0.55	0.52	0.55
50%	0.34	0.32	0.31	0.32
70%	0.45	0.44	0.41	0.43

6. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that a USB Breakout Controller–based CNC system can deliver accurate, stable, and repeatable machining performance for wood fabrication, achieving dimensional deviations of 0.32–0.55 mm and identifying the 50% feed-rate setting as the most effective in balancing accuracy, surface finish, and machining efficiency. The observed 0.04 mm positioning error confirms the reliability of the USB-based motion-control architecture, supporting previous findings on the importance of controller stability in CNC applications while contributing new evidence for its viability in low-cost systems. These results advance the development of affordable CNC platforms and indicate promising directions for future research, including testing additional materials, implementing real-time monitoring, and exploring closed-loop motor control to further enhance machining precision.

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