# Development of a Mini CNC Milling Machine for Educational Purposes at JMTI

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The continuous advancement of modern manufacturing requires highly skilled personnel proficient in Computer Numerical Control (CNC) technology, making it an essential component of Technical and Vocational Education and Training (TVET). However, hands-on training is often limited by the high capital cost, large footprint, and maintenance complexity of industrial CNC machines. This study reports the design, fabrication, and performance evaluation of a Mini CNC Milling Machine developed as a compact and affordable training tool for the Japan-Malaysia Technical Institute (JMTI). The machine was designed using Autodesk Inventor and fabricated from aluminium 6061 through in-house processes including CNC milling and Wire Electrical Discharge Machining (WEDM), followed by anodizing for durability. The control system utilised an Arduino platform running the Grbl open-source G-code interpreter firmware to enable simplified G-code execution. Performance validation included motion accuracy testing, Manual Data Input (MDI) functionality assessment, and cutting accuracy evaluation. Motion testing using a 0.01 mm resolution dial gauge showed a maximum deviation of ±0.05 mm. The MDI test confirmed stable and immediate system response without errors. Cutting trials on acrylic (15 mm × 20 mm geometry) achieved an average dimensional deviation of ±0.01 mm. The results demonstrate that the developed system provides adequate precision for CNC programming education, prototyping, and light-duty machining applications.

## 1.Introduction

The modern manufacturing industry places a strong emphasis on proficiency in Computer Numerical Control (CNC) technology, making it a critical component of Technical and Vocational Education and Training (TVET) curricula (Tung et al., 2021). Institutions such as the Japan-Malaysia Technical Institute (JMTI) are tasked with producing technically competent graduates capable of operating CNC systems in industrial environments. CNC machines, controlled automatically by a computer, allow the creation of products with specified shapes and sizes. The integration of CAD/CAM systems with CNC machining enables high precision, repeatability, and automation in modern manufacturing processes. However, commercial CNC machines are typically large, complex, and expensive, making it difficult for educational institutions to acquire sufficient units for hands-on learning. A major challenge in CNC education is the high cost of ownership and maintenance of full-sized industrial CNC machines, which also require large operating spaces and significant energy consumption (Ali & Mohsin, 2021). These constraints limit practical exposure and reduce opportunities for students to develop operational competency.

Several studies have reported the development of low-cost mini CNC systems using open-source controllers and compact mechanical designs (Barik et al., 2023). While these systems demonstrate technical feasibility, many studies focus primarily on fabrication processes or controller implementation rather than comprehensive system validation. In particular, limited research provides integrated benchmarking of motion accuracy, manual control stability, and dimensional cutting precision within an educational training context. Furthermore, quantitative justification of acceptable tolerance ranges for CNC learning applications remains insufficiently discussed in existing literature. Therefore, this study aims to design, fabricate, and systematically validate a Mini CNC Milling Machine tailored for educational deployment at JMTI. Unlike previous studies that emphasize construction aspects, this research incorporates structured performance evaluation—including motion accuracy testing, Manual Data Input (MDI) validation, and cutting dimensional analysis—to determine the machine's suitability for CNC programming instruction and light machining applications. The findings contribute practical performance benchmarks for low-cost CNC systems within TVET environments.

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# 2. Literature Review

## 2.1 The Evolution and Role of CNC Technology

The history of Computer Numerical Control (CNC) machines traces back to the mid-20th century with the development of Numerical Control (NC) systems, pioneered in the 1940s to improve the precision of complex component manufacturing, particularly in aerospace applications. The early implementation of NC machines marked a significant transition from manual machining toward automated precision manufacturing. The subsequent integration of microprocessors further transformed NC systems into modern CNC machines capable of executing programmed instructions with high repeatability and accuracy.

Today, CNC technology forms the backbone of modern manufacturing systems, enabling high efficiency, precision, and automation. The integration of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) with CNC machining allows the production of complex geometries with tight tolerances. In the context of Industry 4.0, CNC systems continue to evolve with features such as IoT-based monitoring, predictive maintenance capabilities, and intelligent process optimisation (Katduang et al., 2024).

Despite these advancements, industrial-grade CNC machines remain capital-intensive and operationally complex, limiting their accessibility for educational institutions. This limitation has encouraged the exploration of scaled-down CNC systems suitable for training environments.

## 2.2 The Role of Mini CNC Machines in Technical Education

Modern technical education requires hands-on exposure to CNC programming and machining operations. However, traditional industrial CNC machines present challenges due to high acquisition costs, space requirements, and maintenance demands (Ali & Mohsin, 2021). These constraints reduce machine availability and restrict practical student engagement.

In response, several studies have reported the development of Mini CNC Machines using cost-effective components such as stepper motors, ball screws, and open-source control platforms (Barik et al., 2023). These systems successfully demonstrate mechanical feasibility and controller implementation using Arduino-based Grbl firmware.

However, many reported studies primarily emphasize fabrication methodology and system assembly rather than comprehensive performance validation. In particular, systematic benchmarking of motion accuracy, manual control stability, and dimensional cutting precision is often limited or insufficiently quantified. Furthermore, acceptable tolerance ranges for educational machining applications are rarely justified with comparative analysis against published performance data.

Reported motion accuracy for low-cost 3-axis mini CNC systems generally falls within ±0.05 mm to ±0.10 mm under controlled conditions (Salam et al., 2020). While these values indicate feasibility for light machining applications, variations in structural rigidity, backlash control, and calibration procedures can significantly influence performance consistency. Therefore, simply demonstrating functionality does not necessarily confirm suitability for structured CNC training unless validated through repeatable and measurable performance testing.

Accordingly, a structured validation framework that integrates motion accuracy assessment, Manual Data Input (MDI) verification, and cutting dimensional analysis is required to determine the practical suitability of mini CNC systems for TVET-based instructional deployment. The following section outlines the systematic methodology adopted in this study to address this need.

# 3. Methodology

The project methodology applies a structured and sequential development approach based on the Waterfall Design Model to ensure systematic execution and performance validation of the Mini CNC Milling Machine. The Waterfall model remains relevant for engineering systems where requirements are clearly defined and design modifications after fabrication are costly and difficult to implement (Sommerville, 2016).

In hardware-based developments such as CNC machine fabrication, dimensional tolerances, mechanical alignment, and structural integration must be finalized prior to assembly to prevent cumulative geometric errors and performance degradation. Structured phase verification and requirement traceability are widely recommended in systems engineering practices for physical system integration and reliability assurance (Kossiakoff et al., 2019)

Furthermore, systematic and stage-based product development is strongly emphasized in classical engineering design methodology, where conceptual design, embodiment design, and detail design must be validated sequentially to ensure functional integrity (Pahl & Beitz, 2013).

Therefore, a sequential phase-based framework was adopted to maintain design consistency throughout mechanical fabrication and control system integration. As illustrated in Figure 1, the development process is organized into distinct stages, beginning with planning and requirement analysis, followed by mechanical and electrical design, fabrication and assembly, and finally testing and performance evaluation. Each stage was completed and validated before proceeding to the subsequent phase to ensure alignment between structural rigidity, motion transmission accuracy, and control stability.

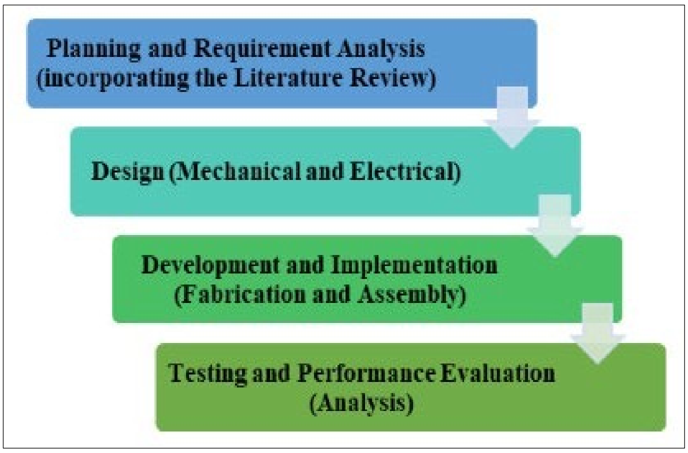


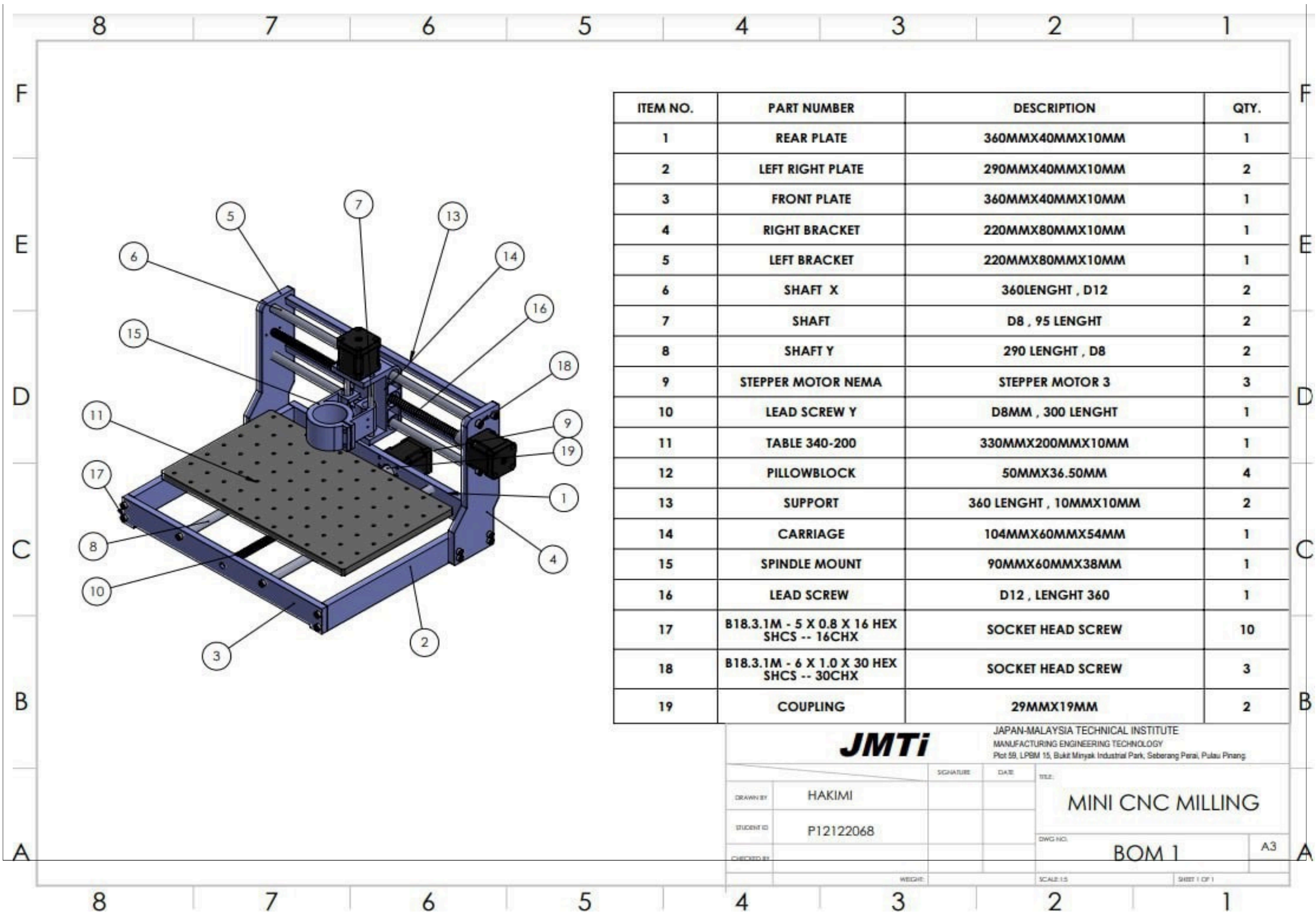
**Figure 1.**Waterfall Design Model

### 3.1 Design and Fabrication

The mechanical design phase was carried out using Autodesk Inventor for three-dimensional modelling, assembly visualization, and Bill of Materials (BOM) preparation. The use of CAD software enabled precise dimensional specification, tolerance control, and alignment verification prior to fabrication.

Accurate digital modelling is essential in small-scale CNC systems, as minor geometric deviations may significantly influence motion accuracy and repeatability. The complete assembly configuration and corresponding Bill of Materials (BOM) generated from the CAD model are presented in Figure 2, illustrating the structural framework, motion transmission components, and major mechanical elements of the Mini CNC Milling Machine.

Aluminium 6061 was selected as the primary structural material due to its favorable strength-to-weight ratio, good machinability, and adequate vibration resistance. In compact CNC platforms, structural rigidity plays a critical role in minimizing deflection and maintaining positional accuracy during cutting operations. Therefore, material selection and frame configuration were carefully considered to balance stiffness, weight, and manufacturability.



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | REAR PLATE | 360MMX40MMX10MM | 1 |
| 2 | LEFT RIGHT PLATE | 290MMX40MMX10MM | 2 |
| 3 | FRONT PLATE | 360MMX40MMX10MM | 1 |
| 4 | RIGHT BRACKET | 220MMX80MMX10MM | 1 |
| 5 | LEFT BRACKET | 220MMX80MMX10MM | 1 |
| 6 | SHAFT X | 360LENGHT , D12 | 2 |
| 7 | SHAFT | D8 , 95 LENGHT | 2 |
| 8 | SHAFT Y | 290 LENGHT , D8 | 2 |
| 9 | STEPPER MOTOR NEMA | STEPPER MOTOR 3 | 3 |
| 10 | LEAD SCREW Y | D8MM , 300 LENGHT | 1 |
| 11 | TABLE 340-200 | 330MMX200MMX10MM | 1 |
| 12 | PILLOWBLOCK | 50MMX36.50MM | 4 |
| 13 | SUPPORT | 360 LENGHT , 10MMX10MM | 2 |
| 14 | CARRIAGE | 104MMX60MMX54MM | 1 |
| 15 | SPINDLE MOUNT | 90MMX60MMX38MM | 1 |
| 16 | LEAD SCREW | D12 , LENGHT 360 | 1 |
| 17 | B18.3.1M - 5 X 0.8 X 16 HEX SHCS -- 16CHX | SOCKET HEAD SCREW | 10 |
| 18 | B18.3.1M - 6 X 1.0 X 30 HEX SHCS -- 30CHX | SOCKET HEAD SCREW | 3 |
| 19 | COUPLING | 29MMX19MM | 2 |

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| DRAWN BY | HAKIMI | | |
| STUDENT ID | P12122068 | | |
| CHECKED BY | | | |

TITLE: MINI CNC MILLING
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WEIGHT:
SCALE 1:5
SHEET 1 OF 1

**Figure 2.** Assembly view and Bill of Materials (BOM) of the Mini CNC Milling Machine

The motion transmission system incorporated stepper motors, ball screws, and linear guide rails to ensure controlled and repeatable axis movement. Ball screws were selected to reduce backlash compared to conventional lead screws, thereby improving positioning precision. Linear guide rails were used to provide smooth translational motion and maintain axis alignment under operational loading conditions.

The electrical control system was designed using an Arduino microcontroller integrated with Grbl open-source firmware. This architecture was selected due to its cost-effectiveness, compatibility with standard G-code commands, and suitability for educational applications. The overall electrical integration, including the Arduino controller, A4988 stepper motor drivers, regulated power supplies, and limit switches, is illustrated in Figure 3, which presents the complete circuit schematic of the system. The system also incorporated a regulated power supply and limit switches to enhance operational safety and motion boundary control.

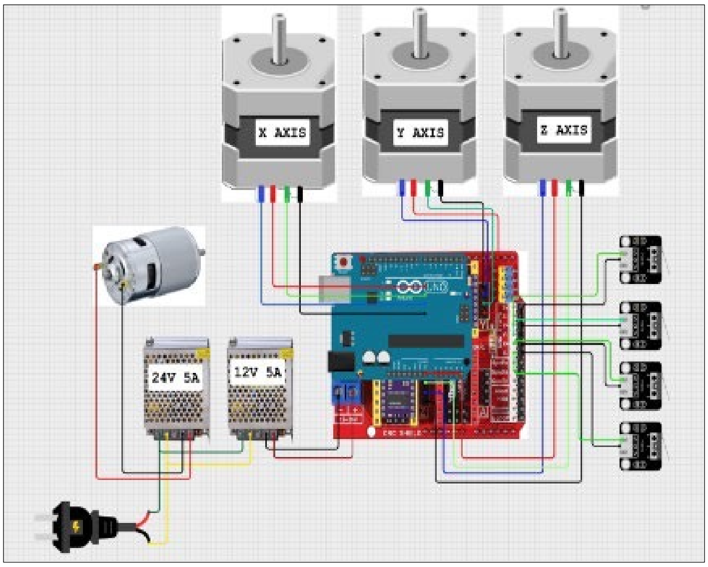

**Figure 3.**Electrical control schematic of the Mini CNC Milling Machine

Fabrication was conducted using in-house machining facilities, including CNC milling, CNC turning, and Wire Electrical Discharge Machining (WEDM). A final anodizing process was applied to aluminium components to improve surface durability and corrosion resistance. During assembly, careful alignment of ball screws and linear rails was performed to minimize geometric errors and cumulative tolerance deviations, which are critical factors affecting motion accuracy in small-scale CNC systems.

## 3.2 Testing and Performance Evaluation

Performance validation of the developed Mini CNC Milling Machine was conducted through three structured assessments: motion accuracy testing, Manual Data Input (MDI) functionality evaluation, and cutting accuracy verification. This multi-stage validation framework was implemented to ensure that both mechanical precision and control stability were systematically evaluated prior to confirming machining capability. The structured testing approach directly addresses the research gap identified in previous studies, where integrated benchmarking of mini CNC systems is often limited or insufficiently quantified.

### 3.2.1 Motion Accuracy Test

Motion accuracy testing was performed to evaluate the positional precision of the X, Y, and Z axes. Controlled displacement commands of 5 mm, 10 mm, and 15 mm were executed through the MDI interface. Actual displacement was measured using a 0.01 mm resolution dial gauge to ensure precise verification. The measurement setup for each axis is illustrated in Figure 4, where the dial gauge was securely mounted to provide direct linear displacement readings along the X, Y, and Z directions.

The dial gauge was positioned in direct contact with the moving carriage of each axis to minimize measurement error and eliminate lateral misalignment effects. Care was taken to ensure stable mounting and to reduce external vibration during measurement. Multiple readings were recorded for each displacement command to verify repeatability and consistency of the motion system. The resolution of the dial gauge (0.01 mm) ensures that the measurement uncertainty remains significantly lower than the observed deviation range, thereby enhancing the reliability of the recorded data.

The maximum deviation recorded did not exceed ±0.05 mm, with the Z-axis exhibiting the highest observed variation. This deviation range is consistent with reported performance levels of low-cost mini CNC systems, typically between ±0.05 mm and ±0.10 mm under controlled laboratory conditions (Salam et al., 2020). Therefore, the achieved motion accuracy is considered acceptable for CNC programming instruction, light machining, and educational prototyping applications. Minor deviations may be attributed to ball screw backlash, microstepping resolution of the stepper motors, and structural compliance of the compact frame design.

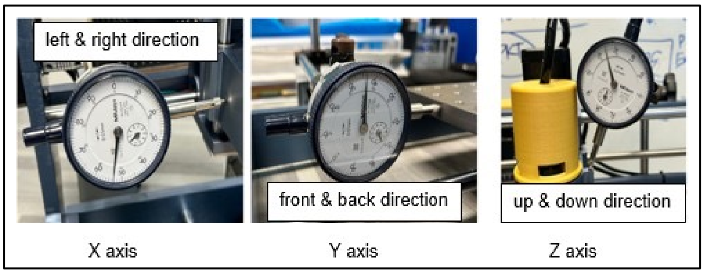

**Figure 4.** Motion accuracy measurement setup using a 0.01 mm dial gauge for X, Y, and Z axes

### 3.2.2 Manual Data Input (MDI) Functionality Test Tables and Figures

The MDI functionality test was conducted to evaluate the responsiveness and stability of the control system. Standard G-code commands including rapid positioning (G00), linear interpolation (G01), spindle activation (M03), and spindle stop (M05) were executed. Each command was tested across all axes to confirm synchronized motion behavior and reliable spindle response.

All commands were processed without observable delay, skipped steps, or execution errors. Immediate axis response and stable spindle activation confirmed effective communication between the Arduino controller, Grbl firmware, and A4988 motor drivers. Verification of manual command stability is particularly important in educational CNC systems, as students frequently rely on MDI inputs for initial setup, calibration, and program testing before executing full machining cycles.

### 3.2.3 Cutting Accuracy Test

To evaluate actual machining performance, a 15 mm × 20 mm rectangular profile was milled on acrylic material using controlled machining parameters (feed rate: 400 mm/min; spindle speed: 2000 rpm; depth of cut: 0.5 mm per pass). The target cutting geometry is illustrated in Figure 5, which presents the designed rectangular profile used for dimensional verification.

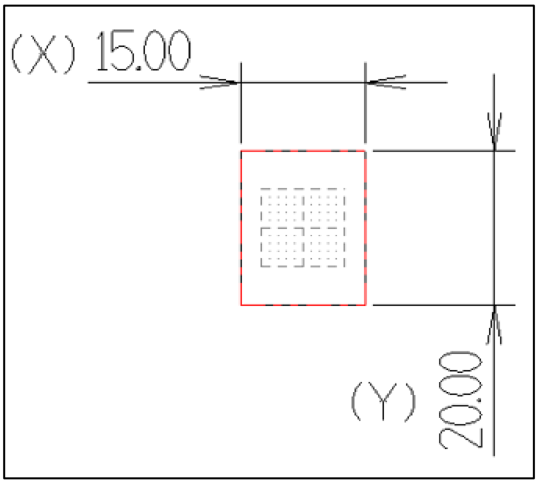

**Fig. 5:** Target rectangular geometry (15 mm × 20 mm) used for cutting accuracy evaluation

The geometry was selected due to its simple orthogonal configuration, allowing precise assessment of linear interpolation accuracy along both X and Y axes. The rectangular form enables direct comparison between programmed dimensions and the actual machined output, thereby providing a clear evaluation of geometric fidelity and motion synchronization during cutting operations.

Following machining, dimensional measurements were performed to determine deviation from the intended geometry. The machined workpiece was first captured using a calibrated digital imaging setup. Dimensional analysis was subsequently conducted using ImageJ software, an open-source image processing tool widely applied for scientific image measurement and geometric analysis (Schneider et al., 2012). Prior to measurement, pixel-to-length calibration was performed using a reference scale to ensure accurate dimensional conversion. The use of digital image-based measurement minimizes human reading error commonly associated with manual calipers and enhances repeatability and consistency in dimensional verification. The measured average dimensional deviation was approximately ±0.01 mm. The relatively lower cutting deviation compared to the maximum motion deviation suggests stable feed execution and consistent motion control during material removal.These results indicate that the developed Mini CNC Milling Machine is capable of maintaining acceptable geometric accuracy for CNC programming education, prototyping activities, and light-duty machining applications.

## 4. Result and Discussion

This section presents the experimental results obtained from motion accuracy testing, Manual Data Input (MDI) validation, and cutting performance evaluation. The findings are analysed and compared with previously reported mini CNC system performance to determine the suitability of the developed machine for educational deployment.

### 4.1 Motion Accuracy Test Result

The motion accuracy test results for the X, Y, and Z axes are summarized in Table 1, while the variation of positional error with respect to displacement distance is illustrated in Figure 6.

**Table 1:** Measured positional displacement and average motion error for X, Y, and Z axes

| Commanded Displacement (mm) | X-axis Measured (mm) | Y-axis Measured (mm) | Z-axis Measured (mm) |
|---|---|---|---|
| 5 | 4.98 | 5.02 | 4.97 |
| 10 | 9.95 | 10.03 | 9.92 |
| 15 | 15.02 | 14.96 | 15.01 |
| **Average Error (mm)** | **±0.03** | **±0.04** | **±0.05** |

Based on Table 1, minor deviations were observed across all axes for commanded displacements of 5 mm, 10 mm, and 15 mm. The average motion error recorded was ±0.03 mm for the X-axis, ±0.04 mm for the Y-axis, and ±0.05 mm for the Z-axis. Among the three axes, the Z-axis exhibited slightly higher variation, which may be attributed to gravitational loading effects and vertical structural compliance due to spindle mass and carriage weight distribution. The maximum deviation of ±0.05 mm at a commanded displacement of 15 mm corresponds to approximately 0.33% relative positioning error, indicating stable motion transmission and consistent mechanical alignment. This low percentage deviation demonstrates that cumulative geometric errors remain well-controlled within the compact structural configuration of the machine.

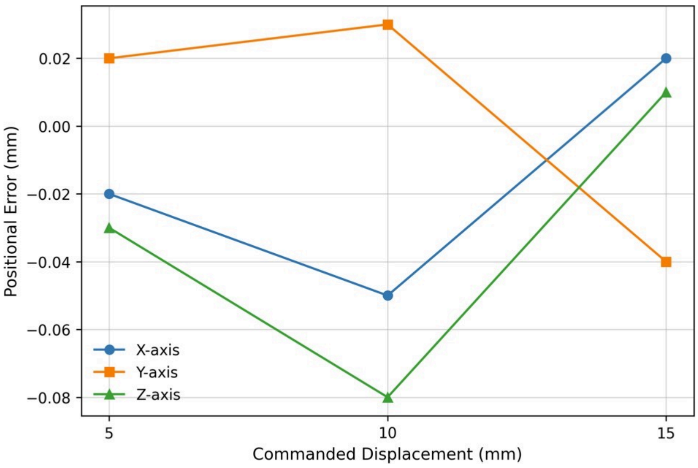

Figure 6. Motion error variation with respect to commanded displacement distance

As illustrated in Figure 6, the positional error does not increase proportionally with displacement distance. Instead, slight fluctuations are observed, particularly at 15 mm displacement for the Z-axis. This behavior suggests that error magnitude is influenced primarily by mechanical backlash, microstepping resolution of the stepper motors, and minor structural compliance rather than travel distance alone. The maximum deviation recorded did not exceed ±0.05 mm, which aligns with previously reported motion accuracy levels of mini CNC systems developed for educational applications (Tung et al., 2021; Salam et al., 2020). Compared to these reported values, the developed system performs within acceptable educational tolerance limits.

Repeated measurements confirmed consistent positioning behavior across multiple trials, indicating stable mechanical integration and reliable motion control. For CNC programming instruction and light-duty machining applications, a tolerance range within ±0.05 mm is considered acceptable, as micron-level industrial precision is not the primary requirement in educational environments.

### 4.2 Manual Data Input (MDI) System Stability

The Manual Data Input (MDI) functionality test was conducted to evaluate the responsiveness and operational stability of the control system. Standard G-code commands, including rapid positioning (G00), linear interpolation (G01), spindle activation (M03), and spindle stop (M05), were executed through the control interface.

The summarized test results are presented in Table 2. All axis movement commands for the X, Y, and Z directions were executed successfully without observable delay. Spindle activation and deactivation commands were also performed consistently. No motion execution errors or communication interruptions were detected during testing

**Table 2:** Results of Manual Data Input (MDI) functionality test

| Function | Result |
|---|---|
| Axis Movement (X, Y, Z) | Successful without delay |
| Spindle Control | Successfully started and stopped |
| Movement Errors | None |

The stable execution of MDI commands indicates effective communication between the Arduino controller, Grbl firmware, and A4988 stepper motor drivers. Reliable manual command processing is particularly important in educational CNC environments, where students frequently utilize MDI inputs during machine setup, zero referencing, and preliminary program verification.

Overall, the findings confirm that the developed Mini CNC Milling Machine exhibits stable and reliable control performance suitable for CNC programming instruction and laboratory-based machining activities.

### 4.3 Cutting Accuracy Evaluation

The cutting accuracy test was conducted to evaluate the machining performance of the developed Mini CNC Milling Machine. A rectangular geometry of 15 mm × 20 mm was milled on acrylic material under controlled machining parameters. The target cutting geometry used for dimensional verification is shown in Figure 5. The dimensional measurements obtained from five cutting samples are summarized in Table 3, while the dimensional consistency across samples is illustrated in Figure 7. Based on Table 3, the measured X-dimension values ranged between 14.96 mm and 15.02 mm, while the Y-dimension values ranged between 19.98 mm and 20.05 mm. The average measured dimensions were 14.99 mm (X-direction) and 20.01 mm (Y-direction), with corresponding average errors of approximately ±0.01 mm.

**Table 3:** Measured dimensional results of cutting accuracy test

| Sample | Target Dimension (mm) | Measured X (mm) | Measured Y (mm) | X Error (mm) | Y Error (mm) |
|---|---|---|---|---|---|
| 1 | 15 × 20 | 14.96 | 20.02 | 0.04 | -0.02 |
| 2 | 15 × 20 | 15.01 | 19.98 | -0.01 | 0.02 |
| 3 | 15 × 20 | 14.97 | 19.99 | 0.03 | 0.01 |
| 4 | 15 × 20 | 15.02 | 20.02 | -0.02 | -0.02 |
| 5 | 15 × 20 | 14.98 | 20.05 | 0.02 | -0.05 |
| Average | — | 14.99 | 20.01 | ±0.01 | ±0.01 |

As illustrated in Figure 7, the dimensional variation across all five samples remains minimal and consistent. The fluctuation pattern does not indicate progressive dimensional drift, suggesting stable motion control and consistent feed execution during material removal.

The recorded average cutting deviation of ±0.01 mm is lower than the maximum motion deviation observed in Section 4.1 (±0.05 mm). This indicates that the machine maintains stable geometric fidelity during actual machining conditions. The achieved cutting precision falls within acceptable tolerance limits for educational CNC programming, prototyping tasks, and light-duty machining applications.

Overall, the results confirm that the developed Mini CNC Milling Machine demonstrates consistent and reliable cutting performance suitable for instructional deployment in TVET environments.

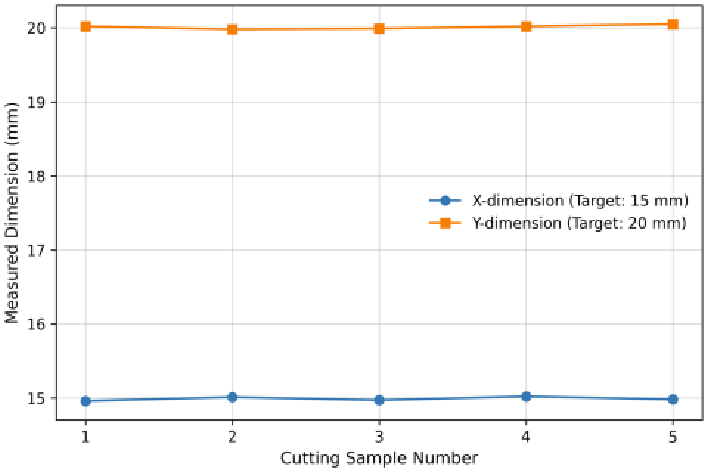

**Figure 7.** Measured dimensional variation across five cutting samples

## 5. Conclusion

This study presented the design, fabrication, and systematic performance evaluation of a Mini CNC Milling Machine developed for educational application at the Japan-Malaysia Technical Institute (JMTI). The development process followed a structured Waterfall Design Model to ensure systematic integration between mechanical design, electrical control architecture, and performance validation. The motion accuracy test demonstrated that the maximum positional deviation did not exceed ±0.05 mm, corresponding to a relative positioning error of approximately 0.33% at maximum displacement. This performance is consistent with reported accuracy ranges of low-cost mini CNC systems in existing literature (Salam et al., 2020). The Manual Data Input (MDI) evaluation confirmed stable and error-free execution of essential G-code commands, indicating reliable communication between the Arduino controller, Grbl firmware, and stepper motor drivers.

Cutting accuracy assessment on a 15 mm × 20 mm rectangular geometry yielded an average dimensional deviation of approximately ±0.01 mm. The consistency of cutting results across multiple samples suggests stable motion control and effective structural alignment during machining operations.

Unlike many previously reported mini CNC developments that primarily emphasize fabrication feasibility, this study incorporated structured benchmarking across motion accuracy, manual control validation, and cutting precision. The results confirm that the developed system achieves acceptable tolerance levels for CNC programming education, basic prototyping, and light-duty machining applications.

Although the developed machine is not intended to replace industrial-grade CNC systems, it provides a compact, cost-effective, and functionally reliable alternative suitable for TVET laboratory deployment. Future work may include long-term durability testing, dynamic load analysis, and expanded machining trials on different materials to further enhance system validation.

## 6. Implications and Recommendations

### 6.1 Implications for Education and Industry

The findings of this study provide meaningful practical implications for both technical education institutions and small-scale industrial applications. The developed Mini CNC Milling Machine offers a cost-effective training platform that enables a larger number of students to gain hands-on experience in CNC programming, machine setup, and basic machining operations. In TVET environments, accessibility to practical equipment plays a critical role in skill development; therefore, the compact and affordable configuration of the system supports broader instructional deployment. Beyond educational use, the developed system may also serve Small and Medium-sized Enterprises (SMEs) that require low-cost solutions for light machining tasks, prototyping, and small-batch production where high industrial precision is not essential.

### 6.2 Recommendations for Enhancement

Although the developed machine achieved acceptable performance levels, several improvements may further enhance its accuracy and structural robustness. To improve motion accuracy, the use of higher-grade ball screws with reduced backlash is recommended. Additionally, the integration of a position encoding system (encoder) could enhance real-time axis position feedback and improve movement verification capability. To enhance structural stability, future designs should consider upgrading frame material rigidity and improving linear rail alignment precision during assembly. Structural reinforcement and optimized mounting techniques may further reduce vibration during machining operations.

### 6.3 Future Development

Future research should focus on expanding system capability through the development of advanced control strategies, including closed-loop motion control and improved motion calibration techniques. Integration with Industry 4.0 technologies, such as remote monitoring and performance data logging, may further enhance system functionality and educational relevance.

## ACKNOWLEDGEMENT

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## REFERENCES

Ali, S. M., & Mohsin, H. (2021). Design and fabrication of 3-axes mini CNC milling machine. IOP Conference Series: Materials Science and Engineering, 1094(1), 012005. https://doi.org/10.1088/1757-899x/1094/1/012005

Barik, S., Thakur, A., & Sharma, P. (2023). Design and fabrication of a compact CNC milling system using open-source control architecture. Materials Today: Proceedings, 72, 1450–1456.

Katduang, S., Panyathip, P., & Wongchai, A. (2024). Integration of Industry 4.0 technologies in CNC machining systems: A review. Journal of Manufacturing Systems, 72, 310–325.

Kossiakoff, A., Sweet, W., Seymour, S., & Biemer, S. (2019). Systems engineering principles and practice (3rd ed.). Wiley.

Pahl, G., & Beitz, W. (2013). Engineering design: A systematic approach (3rd ed.). Springer.

Salam, M. A., Rahman, M. M., & Hossain, M. S. (2020). Performance analysis of a desktop CNC milling machine for educational training. Procedia Manufacturing, 46, 564–571.

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. Nature Methods, 9(7), 671–675. https://doi.org/10.1038/nmeth.2089

Sommerville, I. (2016). Software engineering (10th ed.). Pearson.

Tung, H. Y., Lim, S. C., & Rahman, A. A. (2021). CNC education in TVET institutions: Current challenges and opportunities. Journal of Technical Education and Training, 13(2), 45–58.