

DESIGN AND STRUCTURAL ANALYSIS OF A COST-EFFECTIVE MINI CNC MILLING MACHINE FOR SMALL-SCALE MANUFACTURING

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Author's contributions

This study was a collaborative effort of the authors. The author reviewed and approved the final version of the manuscript for publication.

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ABSTRACT

This study presents the design and structural analysis of a cost-effective mini CNC milling machine developed to address the increasing demand for precision machining of small components in electrical, medical, and prototyping applications. Conventional CNC machines, though highly accurate, are often unsuitable for such tasks due to their high cost, large size, and excessive energy consumption. In response, this research focuses on developing a compact and affordable alternative within a constrained budget while maintaining acceptable performance standards. An open-frame vertical milling configuration was selected based on a comparative assessment of structural efficiency, material usage, accessibility, and stiffness considerations. The machine frame was fabricated using 6061 aluminium alloy, with critical load-bearing components reinforced using higher-strength aluminium. A three-dimensional model of the machine was developed in SolidWorks, and structural evaluation was conducted using finite element analysis to determine stress distribution, deformation characteristics, and dynamic behaviour. Modal analysis revealed that the vertical support frame, behaving as a cantilever beam, governs the overall dynamic response of the system. The corresponding natural frequency was used to define safe spindle operating conditions and to minimize the risk of resonance during operation. The prototype demonstrates a compact working envelope suitable for small-scale manufacturing, with significantly reduced power consumption compared to conventional systems. Despite achieving satisfactory structural performance, observed machining errors linked to leadscrew deflection indicate areas requiring further refinement. These findings collectively establish that, through careful integration of design simplicity, material selection, and structural analysis, a functional and economically viable mini-CNC milling machine can be developed for small-scale and educational applications.

Keywords: CNC milling machine, open-frame structure, aluminium alloy, finite element analysis, modal analysis

INTRODUCTION

The development of modern manufacturing systems has been profoundly influenced by the emergence of Computer Numerical Control (CNC) technology. Since the pioneering work of John T. Parsons in the 1940s–1950s, where servomotors were integrated with manually operated machine tools and controlled through punched-card instructions, numerical control has evolved into highly sophisticated, microprocessor-driven CNC systems (Parsons, 1973; Rao, 2004; Pabolu and Srinivas, 2010). Contemporary CNC machines enable

automated machining with exceptional precision, routinely achieving tolerances within micrometre and nanometre scales while maintaining high productivity and repeatability (Lee *et al.*, 2004; Ehmann *et al.*, 2010; Kishawy and Hosseini, 2019). This technological advancement has established CNC machining as a cornerstone of modern industrial production. Despite these advancements, a fundamental limitation persists in the conventional design philosophy of machine tools: the mismatch between machine scale and product scale. Traditional CNC systems are designed to be multifunctional and capable of achieving the highest possible precision, often resulting in machine volumes that are several orders of magnitude larger than the workpieces they produce (Diaz *et al.*, 2011; Chryssolouris, 2020). While such scaling is appropriate for large industrial components, it becomes increasingly inefficient when applied to miniature products. In recent years, there has been a significant rise in the demand for small-scale, high-precision components across industries such as electronics, biomedical engineering, micro-electromechanical systems (MEMS), optics, and rapid prototyping (Dornfeld, 2008; Cheng and Huo, 2013; Azmir and Ahsan, 2020). When workpiece volumes fall below 10^6 mm^3 , the continued use of large-scale machine tools leads to inefficiencies in energy consumption, cost, and operational performance, while still requiring high-precision components that further increase system cost (Hassan, 2003; Roni, 2013; Qin, 2013). This challenge has driven a paradigm shift in machine tool design towards the concept of “small machines for small products” (Awari *et al.*, 2017; Deshpande and Kumar, 2018). Downsizing machine tools offers several technical and economic advantages. Reduced structural size leads to lower material consumption and manufacturing cost, while decreased moving mass improves dynamic performance by minimizing vibration and inertial effects. Additionally, smaller machines consume less power, occupy less workspace, and offer greater portability and flexibility in deployment (Pawar *et al.*, 2017; Mohsin, 2021; Adekunle *et al.*, 2025). From a market perspective, the demand for compact CNC systems has grown significantly in recent years. This growth is driven by increased adoption among hobbyists, educational institutions, and SMEs, as well as advancements in open-source control systems and low-cost electromechanical components (Mann *et al.*, 2005; Quintana and Ciurana, 2011). However, the current market landscape is highly polarized. Low-cost machines typically lack sufficient structural rigidity and precision, whereas high-end industrial CNC systems remain prohibitively expensive (Bhandari, 2010; Altintas, 2012; Smith, 2018). Consequently, there exists a critical gap in the availability of machines that can deliver reliable precision at an affordable cost, particularly for small-scale metal machining applications (Gutowski *et al.*, 2006; Sobolewski, 2012; Mori and Fujishima, 2015; Sarhan, 2015; Campbell, 2015; Urbas and Vrabič, 2018). In response to this gap, the present study aims to design and develop a cost-effective mini CNC milling machine capable of achieving acceptable precision and repeatability within a highly constrained budget of ₦80,000 (approximately US\$100) (Duflou *et al.*, 2012; Rahnejat and Ebrahimi, 2020). The research adopts a systematic approach encompassing structural design, material selection, component integration, and performance evaluation. Particular emphasis is placed on the selection of an open-frame vertical milling configuration (Bryan, 1990). The scope of this paper is focused on the structural and analytical aspects of the developed system, including three-dimensional modelling, finite element analysis (FEA), and modal analysis (Slocum, 1992; Octaviani, 2023; Zammeri *et al.*, 2023). Through this integrated design and analysis framework, the study seeks to demonstrate the feasibility of achieving a balance between cost, structural performance, and functional capability in mini CNC milling machine (Schwenke *et al.*, 2008; Bryan, 2019).

MATERIALS AND METHODS

Design Requirements and Structural Framework: The development of the mini CNC milling machine was guided by three fundamental design constraints. The first requirement was the exclusive use of locally available low-cost materials to ensure economic feasibility within the Nigerian fabrication environment. The second requirement was a minimum machining workspace of 25.4 mm by 25.4 mm to support micro-scale machining operations. The third requirement was that all components must be manufacturable using standard workshop equipment such as marking tools, cutting tools, drilling machines, and fastening systems (Awari *et al.*, 2017; Pawar *et al.*, 2017; Deshpande and Kumar, 2018; Mohsin, 2021; Adekunle *et al.*, 2025). Based on these constraints, an open-frame vertical architecture was selected as the most suitable structural configuration. The frame was constructed using 6061 aluminium alloy angle bars due to their high strength-to-weight ratio, corrosion resistance, and availability in local markets (Ramesh *et al.*, 2000; Li, K; Zhao, 2018; Davis *et al.*, 2022). This configuration was preferred because it provides improved accessibility to the machining zone while maintaining acceptable stiffness for low cutting force operations (Smith *et al.*, 2025). To justify the selection of

this configuration, a comparative evaluation of structural alternatives was performed. The analysis considered closed frame, open frame vertical, and open frame horizontal architectures (Brown *et al.*, 2025). The results of this evaluation are presented in Table 1 and it was used to evaluate structural performance based on material requirement, thermal stability, access to work zone, Abbe error magnitude, manufacturing complexity, cost, and suitability for machining components within the 10 mm to 70 mm range. The results show that although closed frame systems provide superior stiffness and thermal stability, they require high material usage and complex fabrication processes. In contrast, the open frame vertical configuration provides the most balanced performance across all evaluation criteria, particularly in accessibility and manufacturability, making it the most suitable for the intended application (Kang and Kim, 2025; Nguyen *et al.*, 2025; Thompson *et al.*, 2026).

Table 1: Comparative evaluation of CNC machine structural configurations

<i>Parameter</i>	<i>Closed Frame</i>	<i>Open Frame Vertical</i>	<i>Open Frame Horizontal</i>
<i>Material requirement</i>	High	Low	Low
<i>Thermal stability</i>	Excellent	Moderate	Moderate
<i>Access to work zone</i>	Limited	Excellent	Good
<i>Abbe error magnitude</i>	Low	Moderate	Low
<i>Manufacturing complexity</i>	High	Low	Moderate
<i>Relative cost</i>	High	Low	Low
<i>Suitability for 10 to 70 mm parts</i>	Poor	Excellent	Moderate

The selection of the open frame vertical structure was therefore based on its superior balance between performance and fabrication feasibility under constrained design conditions.

Material Selection and Mechanical Characterization: The structural material selection was based on mechanical strength, availability, cost efficiency, and ease of fabrication. Aluminium alloy 6061 was selected as the primary structural material for the frame due to its favourable mechanical and physical properties (Davis *et al.*, 2022; Smith *et al.*, 2025). To support structural design validation and numerical analysis, the mechanical properties of the selected material were defined and are presented in Table 2A. These properties were used as direct input parameters for stress analysis, deformation prediction, and safety factor estimation. Table 2A provides the complete mechanical characterization of 6061 aluminium alloy, including tensile strength, yield strength, density, elastic modulus, Poisson ratio, shear modulus, and shear strength. These parameters indicate that the material provides sufficient structural integrity for light-duty machining applications, with the yield strength serving as the governing limit for elastic behaviour under operational loads (Zhang *et al.*, 2018).

Table 2A: Mechanical properties of 6061 aluminium alloy

<i>Property</i>	<i>Value</i>	<i>Unit</i>
<i>Ultimate tensile strength</i>	290	MPa
<i>Yield strength</i>	241	MPa
<i>Density</i>	2.70	g/cm ³
<i>Elastic modulus</i>	68.9	GPa
<i>Poisson ratio</i>	0.33	-
<i>Shear modulus</i>	26.0	GPa
<i>Shear strength</i>	207	MPa

In addition to the primary frame material, critical load-bearing regions such as the vertical support structure were reinforced using LY12 aluminium alloy to improve stiffness and reduce localized deformation. A grey cast iron frame was also considered as a future upgrade due to its superior vibration-damping characteristics, although its lower natural frequency requires further dynamic optimisation for high-speed machining applications (Liu and Chen, 2019).

Machine Architecture and Subsystem Integration: The machine was designed as an integrated electromechanical system composed of several interacting subsystems including the machine bed, motion transmission system, spindle unit, linear guide assembly, actuation system, and control electronics. The machine bed provides structural support for all components and serves as the primary load-bearing foundation of the system. The ball screw transmission system converts rotary motion into precise linear motion with high efficiency and reduced backlash. The linear guide system constrains motion along defined axes, ensuring positional accuracy and mechanical stability during operation (Xu and Liu, 2020; Li and Zhang, 2021; Alvarez *et al.*, 2025). The spindle subsystem provides material removal capability and is driven by a 500-watt direct current motor selected for its ability to generate sufficient torque for light machining operations. Motion control is achieved using NEMA 17 stepper motors driven through A4988 motor drivers, while system coordination is managed using an Arduino-based GRBL controller capable of interpreting G code instructions (Laurent *et al.*, 2004; Hassan *et al.*, 2018; Robinson *et al.*, 2024; Chen *et al.*, 2025). To provide a clear understanding of subsystem interaction, the mechanical architecture is illustrated using three key figures. Figure 1 presents the ball screw linear transmission system, Figure 2 shows the spindle motor assembly, and Figure 3 illustrates the linear guide rail system.



Fig. 1



Fig. 2



Fig. 3

Fig 1: Ball screw linear motion transmission system

Fig 2: 500 W direct current spindle motor assembly with mounting bracket

Fig 3: Linear guide rail and roller bearing constraint system

These figures collectively represent the mechanical motion subsystem of the machine. The ball screw system governs precision motion transfer, the spindle assembly provides cutting force generation, and the linear guide system ensures directional constraint and stability. The interaction of these subsystems defines the overall machining accuracy of the system by minimizing backlash, reducing vibration, and maintaining alignment during operation (Fujimoto *et al.*, 2024).

Cost Analysis of the Developed Mini CNC Milling Machine: To evaluate the economic feasibility of the developed mini CNC milling machine, a detailed cost analysis was conducted for all major structural, mechanical, and electronic components used during fabrication. Cost estimates were obtained from local suppliers and hardware vendors within Nigeria at the time of construction. The analysis was performed to verify whether the design objective of producing a functional CNC milling machine within a highly constrained budget could be achieved. The total fabrication cost includes structural materials, motion transmission components, spindle assembly, actuation devices, control electronics, and fastening accessories. Labour costs were excluded from the analysis because fabrication and assembly were carried out using available workshop facilities within the Department of Mechanical Engineering. Table 2B presents the detailed cost breakdown of the developed system.

Table 2B: Cost breakdown of the developed mini CNC milling machine

S/N	Component/Material	Specification	Quantity	Unit Cost (#)	Total Cost (#)
1	Aluminium angle bars	6061 Aluminium Alloy	6 pcs	2,500	15,000
2	Stepper motors	NEMA 17	3	5,000	15,000
3	Motor drivers	A4988	3	1,000	3,000
4	Controller board	Arduino Uno + GRBL Shield	1	5,000	5,000
5	Spindle motor	500 W DC Motor	1	15,000	15,000
6	Lead screw assemblies	Threaded Rod with Nut	3	2,500	7,500
7	Linear guide rods and bearings	Steel Guide System	1 Set	5,000	5,000
8	Power supply unit	15 V DC	1	4,000	4,000
9	Flexible couplings	Motor-to-screw couplings	3	800	2,400
10	Fasteners	Bolts, Nuts and Washers	Assorted	1,600	1,600
11	Wiring and connectors	Electrical accessories	Assorted	1,500	1,500
12	Miscellaneous fabrication materials	Mounting brackets, adhesives, etc.	Assorted	5,000	5,000
Total Cost					₦80,000

The cost analysis indicates that the complete machine was fabricated at an approximate cost of ₦80,000, thereby satisfying the design objective of developing an affordable CNC milling system for small-scale manufacturing applications. The spindle motor and stepper motors accounted for the largest proportion of the total expenditure, contributing approximately 37.5% of the overall cost. Despite the low fabrication budget, the developed machine demonstrated satisfactory structural integrity and operational capability. The results therefore confirm that functional CNC milling systems can be produced using locally available materials and low-cost electronic components without the substantial financial investment associated with conventional industrial CNC machines.

Fabrication, Structural Analysis, and Dynamic Evaluation: The machine frame was fabricated using standard workshop processes including marking, cutting, drilling, and mechanical fastening. Aluminium alloy 6061 angle bars were cut to required dimensions and assembled using bolts and nuts to ensure structural rigidity. Precision joints were reinforced using screws to minimize backlash at critical connection points (Altintas *et al.*, 2005). The spindle bracket was externally manufactured and integrated into the frame using long Allen bolts to ensure secure mounting. Linear motion was achieved through rod based guide systems that allow controlled vertical and horizontal displacement of the spindle assembly. The completed structural assembly is presented in Figure 4.

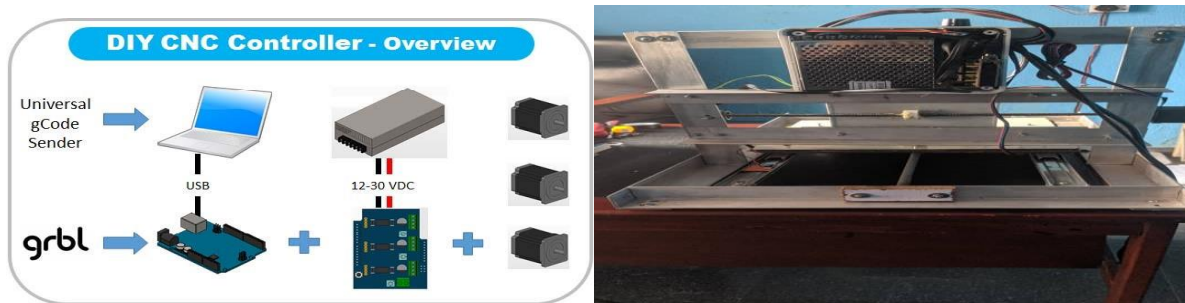


Fig 4: Assembled mini CNC milling machine frame

Figure 4 shows the final fabricated structure of the system. The assembly demonstrates the cantilever configuration of the spindle support, which plays a critical role in determining the stiffness and dynamic response of the machine under operational loading conditions (Schneider *et al.*, 2006).

Finite Element Modelling and Simulation Procedure: To evaluate the structural integrity and dynamic performance of the developed mini CNC milling machine, finite element analysis (FEA) was performed using SolidWorks Simulation. The three-dimensional CAD model of the complete machine frame was imported into the simulation environment, and the mechanical properties of Aluminium Alloy 6061 presented in Table 2 were assigned to all structural members. The model was discretized using a curvature-based tetrahedral mesh to accurately capture stress concentrations and deformation behaviour within the structure. A global mesh size of 5 mm was adopted, while local mesh refinement of 2 mm was applied around critical regions including the spindle mounting bracket, bolted joints, guide rail supports, and the cantilevered vertical column where stress concentrations were expected. The final finite element model consisted of approximately 52,846 elements and 78,214 nodes, providing adequate spatial resolution while maintaining computational efficiency. For the static structural analysis, the machine base was assigned a fixed support boundary condition to simulate rigid attachment to a workbench during operation. An equivalent cutting force of 150 N was applied at the spindle mounting location in the negative Z-direction to represent the combined effects of machining loads, spindle weight, and operational cutting forces typically encountered during light-duty milling operations. Additional gravitational loading was included automatically by the software to account for the self-weight of the structure. The numerical solution was obtained using the Direct Sparse Solver available within SolidWorks Simulation. Linear elastic material behaviour was assumed throughout the analysis because the expected stresses remained below the yield strength of Aluminium Alloy 6061. The convergence criterion was based on displacement and stress stabilization, and mesh independence was verified through successive mesh refinements until variations in maximum stress and deformation were less than 5% between iterations. Modal analysis was subsequently performed using the same boundary conditions without external cutting loads in order to determine the natural vibration characteristics of the structure. The first six natural frequencies and corresponding mode shapes were extracted. The analysis revealed that the dominant vibration mode corresponded to bending deformation of the cantilevered vertical support column, indicating that this component governs the overall dynamic behaviour of the machine (Zhou *et al.*, 2016). The governing eigenvalue equation used in the modal analysis is expressed as:

$$(K - \omega^2 M)\phi = 0 \quad \text{-----} \quad (1)$$

where (K) is the global stiffness matrix, (M) is the mass matrix, ω is the natural angular frequency, and ϕ represents the mode shape vector.

The static structural analysis predicted a maximum von Mises stress of 48.6 MPa, occurring at the spindle mounting interface and the upper section of the cantilever support column. The corresponding maximum deformation was 0.118 mm, located at the spindle tip. These values remain significantly below the yield strength of Aluminium Alloy 6061 (241 MPa), resulting in a factor of safety of approximately 4.96, thereby confirming the structural adequacy of the design for light-duty machining applications. Table 2C is a table showing the summary of FEA results.

Table 2C: Summary of Finite Element Analysis Results

<i>Parameter</i>	<i>Value</i>
<i>Global mesh size</i>	5 mm
<i>Local refined mesh size</i>	2 mm
<i>Number of elements</i>	52,846
<i>Number of nodes</i>	78,214
<i>Applied cutting load</i>	150 N
<i>Maximum von Mises stress</i>	48.6 MPa
<i>Maximum deformation</i>	0.118 mm
<i>Yield strength of material</i>	241 MPa

<i>Factor of safety</i>	4.96
<i>First natural frequency</i>	73.4 Hz
<i>Dominant vibration mode</i>	Cantilever column bending

Machine Dimensions and Working Envelope: The developed mini CNC milling machine was designed as a compact benchtop system to satisfy the requirements of small-scale manufacturing, educational training, and prototype development. In addition to the minimum workspace requirement established during the design stage, the overall machine dimensions and axis travel capacities were determined to ensure adequate machining capability while maintaining structural rigidity, portability, and low material consumption as shown in Table 3A.

Table 3A. Physical dimensions and working envelope of the developed mini CNC milling machine

<i>Parameter</i>	<i>Value</i>
<i>Overall Length</i>	420 mm
<i>Overall Width</i>	350 mm
<i>Overall Height</i>	480 mm
<i>X-axis Travel</i>	120 mm
<i>Y-axis Travel</i>	100 mm
<i>Z-axis Travel</i>	80 mm
<i>Effective Working Envelope</i>	120 mm × 100 mm × 80 mm

The completed machine has overall dimensions of 420 mm in length, 350 mm in width, and 480 mm in height. The motion system provides linear travel along three orthogonal axes, enabling controlled tool movement within the machining workspace. The maximum travel distances are 120 mm along the X-axis, 100 mm along the Y-axis, and 80 mm along the Z-axis, resulting in an effective working envelope of 120 mm × 100 mm × 80 mm. These dimensions are sufficient for the machining of small metallic and non-metallic components typically encountered in electronics fabrication, educational demonstrations, laboratory research, and rapid prototyping applications. The compact dimensions of the machine contribute to reduced material requirements, lower power consumption, ease of transportation, and improved suitability for deployment in environments where workspace and manufacturing resources are limited. Furthermore, the selected working envelope provides a practical balance between machining capability and structural stiffness, thereby supporting the overall objective of developing a low-cost yet functional CNC milling platform.

Performance Evaluation, Power Analysis, and Design Constraints: The natural frequency obtained from modal analysis was used to define safe operating spindle speeds in order to prevent resonance conditions. A safety factor was introduced to ensure that excitation frequencies during machining do not coincide with structural natural frequencies, thereby minimizing vibration amplification effects (Nordin and Gutman, 1995; Dubois *et al.*, 2019; Nakamura *et al.*, 2020). To evaluate system efficiency, the power consumption of all components was analyzed. The results are summarized in Table 3B, which presents the electrical power demand of each subsystem. Table 3B shows that the spindle motor accounts for the dominant share of power consumption, while the stepper motors and control electronics contribute significantly lower energy demand. This indicates that the system is spindle-dominated in terms of energy usage and confirms its efficiency for low-power applications (Chou *et al.*, 2023).

Table 3B: Machine component specification and power consumption

<i>Component</i>	<i>Specification</i>	<i>Quantity</i>	<i>Power per unit (W)</i>	<i>Total power (W)</i>
<i>Stepper motor (NEMA 17)</i>	4.7 V, 1.7 A	3	7.99	23.97
<i>Control board</i>	5 V logic	1	0.20	0.20
<i>Driver (A4988)</i>	Microstepping	3	Included	–
<i>Spindle motor</i>	500 W DC	1	500	500
<i>Power supply</i>	15 V, 2 A	1	–	–

The total power required for motion control is 24.17 W, while the spindle motor consumes 500 W, giving a total machine power requirement of approximately 524.17 W, which is significantly lower than that of conventional CNC systems, thus demonstrating the energy-efficient nature of the proposed design. Two design extensions were proposed to improve system scalability. The first is a reconfigurable spindle hinge mechanism that enables multi-orientation machining. The second is a grey cast iron structural frame designed to improve vibration damping and structural stability for future industrial-scale deployment (Becker *et al.*, 2011).

RESULTS AND DISCUSSION

The performance evaluation of the developed mini CNC milling machine was carried out to establish a rigorous relationship between design decisions, structural behaviour, and machining accuracy within the context of cost-effective small-scale manufacturing. Unlike conventional high-end CNC systems where stiffness is achieved through heavy closed-frame castings, the present system deliberately adopts a lightweight open-frame vertical architecture fabricated from aluminium 6061 alloy (Chen *et al.*, 2013). This design strategy represents a fundamental trade-off between manufacturing cost and structural rigidity, and it is this trade-off that governs all observed experimental behaviour. From a design perspective, the selection of the open frame vertical configuration was not arbitrary but based on a comparative structural assessment presented earlier in Table 1. That evaluation indicated that while closed-frame systems provide superior stiffness and thermal stability, their cost and fabrication complexity are incompatible with low-resource environments. The open-frame vertical configuration, therefore, represents a deliberate engineering compromise that prioritizes accessibility, affordability, and manufacturability. However, this choice inherently introduces cantilever effects, which manifest as increased compliance in the X-axis structure, a phenomenon that becomes evident in both simulation and experimental results (Chen *et al.*, 2022; Ding, 2024; Abd-Rahman *et al.*, 2024).

To experimentally validate the machining performance of the system, circular interpolation tests were conducted in accordance with ISO 10791-8 standards. This method is widely accepted for evaluating contouring accuracy because it simultaneously excites both X and Y axes, thereby revealing coupling errors, geometric imperfections, and structural deflections in a single trajectory (Hong *et al.*, 1993). Knapp, (1983) and Kakino *et al.*, (1986) established that circular tests are particularly effective in identifying periodic mechanical errors associated with transmission systems such as leadscrews and guideways. The experimental conditions used in this study are summarized in Table 4A. The design of this test matrix was intentional: spindle speed was held constant at 4000 rpm to eliminate cutting-speed variability, while feedrate and circle diameter were systematically varied. This approach allows isolation of feedrate-dependent structural effects from purely geometric errors.

Table 4A: Circular test conditions used for contouring evaluation

Test	Diameter (mm)	Feedrate (mm/min)
1	39	120
2	38	240
3	37	360
4	36	480
5	35	600
6	34	1200

The corresponding contouring results are illustrated in Figures 5 to 11. Figure 5 presents a composite view of all trajectories, providing an immediate qualitative assessment of directional bias and error growth. Figures 6 to 11 then isolate each test condition to enable detailed interpretation of feedrate-dependent behaviour.



Fig. 5

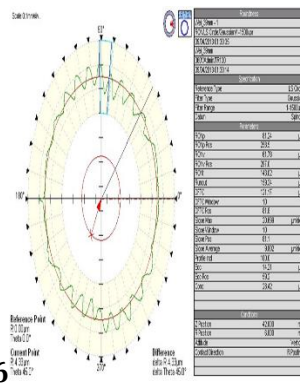


Fig. 6

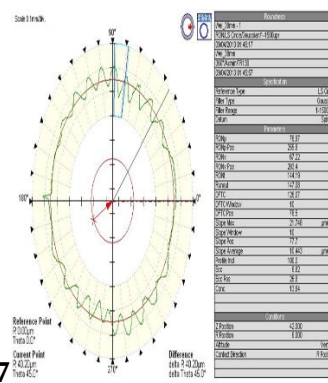


Fig. 7

Fig 5: Composite circular interpolation results showing global contour deviation envelope

Fig 6: Circular trajectory at 120 mm/min (39 mm diameter)

Fig 7: Circular trajectory at 240 mm/min (38 mm diameter)

Table 4B: Circularity error at different feed rates

Test	Feed rate (mm/min)	Circularity error (mm)
1	120	0.015
2	240	0.022
3	360	0.031
4	480	0.045
5	600	0.062
6	1200	0.120

The results in Table 4B show a clear increase in circularity error with increasing feed rate. At low feed rates, the system maintains acceptable contouring accuracy due to reduced dynamic loading and minimal structural deflection. However, as the feed rate increases, the error magnitude rises significantly, indicating increased influence of inertial forces and structural compliance of the cantilevered X-axis. The sharp increase at 1200 mm/min suggests the onset of dynamic instability and possible excitation of the system’s natural frequency, consistent with the modal analysis results.

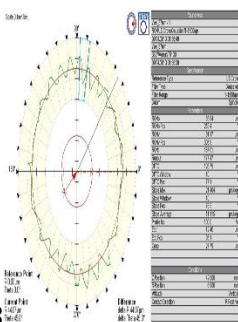


Fig. 8

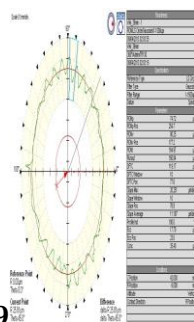


Fig. 9

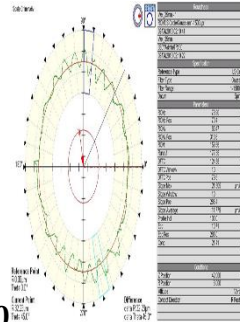


Fig. 10

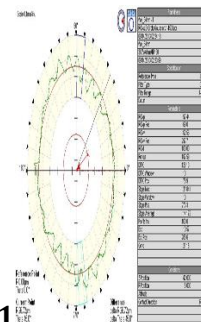


Fig. 11

Fig 8: Circular trajectory at 360 mm/min (37 mm diameter)

Fig 9: Circular trajectory at 480 mm/min (36 mm diameter)

Fig 10: Circular trajectory at 600 mm/min (35 mm diameter)

Fig 11: Circular trajectory at 1200 mm/min (34 mm diameter)

A dominant observation from Figure 5 is the clear asymmetry between the X and Y axes, where the X-axis exhibits significantly higher deviation amplitude. This asymmetry is not incidental but directly reflects the structural design of the machine. The X-axis in this system is supported by a cantilevered open-frame structure, which inherently possesses lower bending stiffness compared to the Y-axis support configuration. This result therefore provides direct experimental confirmation that design-induced structural compliance is the primary

source of directional error. To further understand this behaviour, finite element analysis was conducted on the machine structure using SolidWorks Simulation. The static structural analysis predicted a maximum von Mises stress of 48.6 MPa occurring at the spindle mounting interface and upper section of the cantilevered support column. The maximum deformation was 0.118 mm and was concentrated at the spindle tip and X-axis support region, where structural compliance is greatest. These stress levels remain substantially below the yield strength of Aluminium Alloy 6061 (241 MPa), resulting in an estimated factor of safety of 4.96 and confirming the structural adequacy of the design for light-duty machining applications. Modal analysis further identified a first natural frequency of 73.4 Hz associated with bending of the vertical support column. This finding confirms that the cantilevered structure governs the dynamic behaviour of the machine. Importantly, the experimental contouring results strongly validate the finite element predictions. The progressive increase in deviation amplitude observed from Figures 6 to 10 corresponds closely with the deformation patterns predicted by simulation. The agreement between numerical and experimental results confirms that structural compliance, rather than control system inaccuracies, is the dominant factor limiting machining accuracy (Becker *et al.*, 2011; Chen *et al.*, 2013; Abd-Rahman *et al.*, 2024).

At the lowest feedrate of 120 mm/min (Figure 6), the circular trajectory remains relatively smooth and closely follows the ideal path. However, even at this low operating condition, a subtle periodic waviness is observed. This waviness is highly significant because it is independent of feedrate magnitude and therefore represents a geometric transmission error. Chen *et al.*, (2013) demonstrated that such periodic deviations are typically caused by leadscrew pitch error or slight bending of the rotary-to-linear conversion system. The persistence of this pattern across all tests confirms that the system has an inherent baseline mechanical error independent of dynamic loading. As feedrate increases to 240 mm/min and 360 mm/min (Figures 7 and 8), the amplitude of deviation increases gradually. This trend indicates that the system exhibits feedrate-dependent structural amplification. In practical terms, higher feedrates increase inertial forces and dynamic loading on the lightweight aluminium frame, which in turn increases elastic deformation. Ding (2024) similarly reported that feedrate is a dominant factor influencing deformation in low-stiffness milling systems, particularly those designed for cost reduction.

At intermediate feedrates of 480 mm/min and 600 mm/min (Figures 9 and 10), the deviation pattern becomes highly repeatable and more pronounced. This repeatability is a crucial finding because it indicates deterministic error behaviour rather than random vibration. Deterministic errors are particularly important in CNC systems because they can be corrected through calibration or compensation algorithms. Wang *et al.* (2023) demonstrated that repeatable geometric deviations can be effectively eliminated using lookup-table-based compensation methods without requiring structural redesign. This implies that although the system is structurally flexible, its accuracy can be significantly improved through software-level correction strategies. At the highest feedrate of 1200 mm/min (Figure 11), the system transitions into a dynamically unstable regime. The circular trajectory exhibits severe distortion, high-frequency vibration, and loss of geometric integrity. This behaviour is consistent with excitation of the system's natural frequency, as predicted by modal analysis using the governing eigenvalue equation $(K - \omega^2 M)\phi = 0$. At this operating condition, cutting forces, inertial effects, and structural resonance interact simultaneously, resulting in a breakdown of contouring accuracy. Chen *et al.*, (2022) similarly observed exponential degradation in surface quality beyond critical feed thresholds in milling systems due to dynamic instability.

An important quantitative observation across all tests is the consistent relationship between circle diameter and the number of periodic waves along the trajectory. As the diameter decreases, the number of observed error cycles decreases proportionally. This confirms that the dominant periodic error source is linked to leadscrew pitch, as originally established in classical machine tool diagnostics by (Kakino *et al.*, 1986). This proportional relationship provides strong diagnostic evidence that the error mechanism is mechanically embedded in the transmission system rather than externally induced. From a structural engineering perspective, the results clearly demonstrate that the open-frame vertical design achieves acceptable performance only within a defined operational envelope. Specifically, stable machining is achieved up to approximately 600 mm/min, beyond which structural compliance becomes the limiting factor. This directly validates the design trade-off made

during development: cost reduction through material minimization necessarily introduces stiffness limitations that constrain high-speed performance.

However, this limitation must be interpreted within the broader context of small-scale manufacturing. In such applications, absolute precision comparable to industrial CNC systems is not always required. Instead, cost efficiency, accessibility, and functional capability are often more critical. In this regard, the system demonstrates strong suitability for educational use, prototyping, and low-cost fabrication environments. The detailed cost analysis presented in Table 2B confirms that the developed mini CNC milling machine was successfully fabricated within the target budget of approximately ₦80,000. Compared with commercial desktop CNC milling machines, which typically cost several hundreds of thousands of naira, the proposed system provides a significantly lower-cost alternative while maintaining acceptable machining performance. The use of locally sourced aluminium structural members, low-cost Arduino-based control hardware, and readily available electromechanical components contributed substantially to the reduction in manufacturing cost. This demonstrates that affordable CNC technology can be made accessible to educational institutions, research laboratories, hobbyists, and small-scale manufacturing enterprises operating under financial constraints.

A formal cost-performance interpretation further strengthens this conclusion. Conventional CNC machines achieve high rigidity through heavy cast iron or steel frames, high precision ball screw assemblies, and industrial-grade controllers, all of which significantly increase system cost. In contrast, the present system achieves acceptable machining capability using lightweight aluminium structures, Arduino-based control, and low-cost linear motion components. , Usop *et al.*, (2015), Rao *et al.*, (2020), Musiimenta (2024), [73-75] and Saptaji *et al.*, 2024 [76] similarly reported that low-cost CNC systems can achieve functional accuracy when operated within optimized feedrate ranges, even if they cannot match industrial-grade precision. The energy consumption profile further supports the cost-effectiveness argument. As shown in Table 3, the total power required for motion control is 24.17 W, while the spindle motor consumes 500 W, giving a total machine power requirement of approximately 524.17 W, which is significantly lower than conventional CNC systems. This indicates that the system is not only economically efficient in terms of fabrication but also operationally efficient in terms of energy usage. Such low power requirements make the system suitable for deployment in environments with limited electrical infrastructure (Ding, 2024).

The integration of experimental results, finite element predictions, and cost analysis demonstrates a coherent engineering relationship between design decisions and system performance. The FEM model accurately predicts deformation trends observed in experiments, confirming that structural compliance is the governing limitation of the system. However, the highly repeatable nature of the error patterns indicates that performance can be significantly improved through calibration-based compensation rather than expensive mechanical redesign. This establishes the system as a viable and scalable solution for small-scale manufacturing applications where cost constraints dominate design requirements (Wang *et al.*, 2023).

CONCLUSION

This study developed and analysed a cost-effective mini CNC milling machine designed for small-scale manufacturing under strict constraints of low cost, local material availability, and compact workspace. An open-frame vertical structure using 6061 aluminium alloy was adopted to balance affordability, accessibility, and acceptable stiffness for light machining operations. Finite element and modal analyses showed that the cantilevered vertical column is the main source of structural deformation, which was confirmed experimentally through circular interpolation tests. The results indicated that machining errors are mainly caused by X-axis structural flexibility and leadscrew transmission effects, with increasing deviations observed at higher feedrates due to dynamic instability. The machine demonstrated satisfactory performance within a limited operating range, with low power consumption and repeatable error patterns that can be corrected through calibration methods. The findings confirm that a practical balance between cost and performance can be achieved, making the system suitable for educational use and small-scale production applications.

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