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Research Article

Design and development of a prototype 3-axis CNC wood carving machine

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Abstract
Computer numerical control (CNC) wood carving technology is increasingly becoming an integral part of the wood processing industry in Vietnam, gradually replacing traditional wood carving methods. This technological advancement not only enhances the aesthetic quality of wood products but also significantly reduces production time and labor costs. However, most manufacturers of CNC wood carving machines do not disclose their design processes, making it challenging for users to select machines that meet their specific requirements. This study focuses on the design and development of a small-scale, 3-axis CNC wood carving machine. The objective is to create a machine that is fully functional, efficient, cost-effective, and easy to maintain. The research includes the conceptual design, 3D modeling, and simulation of the machine, emphasizing precision, smooth operation, and minimal error rates. Finite element analysis (FEA) was conducted to validate the structural durability of the 3D model. Following the simulation, a prototype was fabricated and tested. Experimental results demonstrate that the machine can effectively perform a range of tasks—including carving, milling, and drilling—on materials such as wood, mica, and soft metals like aluminium.

Keywords
CNC wood carving, 3-Axis CNC machine, Prototype development, Finite element analysis (FEA), Design and fabrication.

1.Introduction
Wood, as a natural material, provides enduring aesthetic appeal and remarkable adaptability for engraving. The distinctive grains and textures of wood ensure that each engraved piece is unique; even when using the same wood type, variations in natural patterns result in truly one-of-a-kind outcomes for every project. Wood engraving is one of the most popular art forms known to mankind. In ancient times, this craft was performed manually using primitive tools such as chisels and hammers, requiring a significant amount of time and physical labor. Wood engraving technology has made significant advancements over the past decades, evolving from simple mechanical systems to modern engraving machines utilizing computer numerical control (CNC) and laser technology. This development has not only greatly improved the precision and speed of engraving but has also expanded the creative possibilities and flexibility in producing complex decorative and furniture products [1, 2].

There are currently several types of popular wood engraving machines, each suited to different requirements.

First, CNC engraving machines are available in various models, ranging from 3-axis, 4-axis to 5-axis systems [3–6]. The 3-axis CNC machines can move the engraving head along the X, Y, and Z axes, making them suitable for flat surface engraving tasks [6–9]. The 4-axis CNC machines add the A-axis, allowing the engraving head to rotate around the axis to create three-dimensional(3D) details such as wooden statues or columns. Meanwhile, 5-axis CNC machines can control the engraving head to move flexibly along five axes, enabling them to process complex products with high precision without the need to reposition the workpiece. In addition, laser

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engraving machines also play a crucial role in the wood processing industry. CO_2 laser engravers are a popular choice due to their ability to engrave quickly and accurately on a variety of materials. Fiber laser engravers, while primarily used for metals, can also be adjusted to engrave wood with high detail. Moreover, mini engraving machines and handheld engravers are widely favoured by artisans and home users due to their compact size, affordability, and ease of use. These machines are particularly well-suited for engraving small details such as names, symbols, or simple patterns on wood, meeting the demands of craft production or personalizing products. However, all the aforementioned products were either costly or challenging to control. High-quality motors, control systems, and durable cutting tools tend to be expensive, making it difficult to strike a balance between affordability and performance. Moreover, comprehensive design processes are scarcely documented in the existing literature. Research on wood carving machines remains limited, with most available sources comprising technical manuals rather than academic studies, thereby hindering the clear explanation of complex design principles and analytical calculations.

Chen et al. [7] fabricated a laboratory prototype of a 5-axis machining robot for wood carving, which was integrated with a custom-developed control system. However, the overall system design was complex and costly, making it unsuitable for small workshops or educational settings. Tomar and Natarajan [8] proposed a technique for measuring the shape profile of wooden blocks during the chiseling process. Their method involved the use of a processing system based on camera and computer vision techniques to enhance carving precision. However, the integration of such technology poses challenges for mechanical engineers, as it primarily falls under the domain of information technology.

Kannaki et al. [9] developed a multi-purpose 3D printer capable of performing 3D printing, CNC machining, laser engraving, and wood engraving. Nonetheless, their work did not include detailed structural design or durability simulation. In another study, Açık [10] examined the impact of varnish layers on laser wood engraving and found that all types of varnish negatively affected the efficiency of the engraving process. Additionally, Corleto et al. [11] investigated the influence of varying moisture levels on the quality of laser-cut wood, highlighting the importance of environmental factors in the engraving process.

This paper presents the design and development of a small, cost-effective 3-axis CNC wood carving machine that maintains performance and quality comparable to larger machines used in professional woodworking environments. The proposed machine is intended to address the needs of detailed, small-scale wood carving for home use while simultaneously serving as an educational tool. It offers users an opportunity to gain practical knowledge of machine design, structural mechanics, and operational principles, thereby enhancing their skills and understanding in the field of CNC machining.

The remainder of this paper is organized as follows. Section 2 presents a review of the literature on carving technologies. Section 3 outlines the design process of the wood carving machine. Section 4 details the manufacturing process and performance verification of the prototype. Section 5 discusses the impact and limitations of the study. Finally, Section 6 provides the conclusion.

2.Literature review

In order to perform wood carving effectively, the machining of wood materials must be properly executed. Huang et al. [12] developed a method to project two key milling parameters for thermally modified wood. Chen et al. [13] established a foundation for enhancing tool condition monitoring (TCM) applications in the cutting of wood-based materials. Wu et al. [14] investigated the machining of wood-plastic composite materials to improve stability and surface quality.

From the perspective of machine design, Sobri et al. [15] offered practical insights into the optimization of laser parameters for tropical wood species, thereby improving precision in laser machining and supporting sustainable wood processing practices. Wachowicz et al. [16] examined the durability of carbide blades during the cutting of wood materials. Isahak et al. [17] outlined the key challenges facing the wood carving industry. Additionally, Islami et al. [18] explored the design and machining processes of wood carving products using integrated computer aided design (CAD)/computer aided manufacturing (CAM)/CNC technologies.

A CNC wood carving machine operates based on CNC, where commands are encoded into G-code to guide the machine in performing carving and cutting tasks according to a digital design [19, 20]. The process begins with the user creating a digital blueprint using CAD software such as AutoCAD or SolidWorks [21, 22]. This design is then converted into G-code using CAM software. The G-code contains detailed information about the toolpath, cutting speed, and depth of cut, and it is loaded into the CNC machine's control system. Once the machine starts operating, stepper or servo motors control the movement of the cutting head along the X, Y, and Z axes according to the instructions from the G-code. The spindle, which holds the cutting tool, rotates at high speed, making contact with the wood surface and carving it along the programmed paths. This automated control system minimizes human error, increases productivity, and allows the creation of complex designs that would be difficult to achieve with traditional manual methods [23, 24]. After the carving process is complete, the product can be inspected and further finished to achieve the highest aesthetic and quality standards [25, 26].

Based on the literature survey, the key challenges in designing a wood carving machine can be summarized as follows:

- The main spindle speed should be above 10000 round per minute (rpm) in order to cutting wood properly.
- Cutting tool need to be installed firmly and balance, lack of tool stability leads to vibration.
- The design needs to minimize vibration and resonance.
- The precision of product is the first demand but need to consider the overall cost.
- Wood chips could jam the machine components

To address the key challenges in wood carving machine development, various methods have been implemented, focusing on spindle design, structural integrity, precision control, and chip management. A commonly adopted method involves using a high-speed spindle motor—typically rated above 10,000 rpm—to ensure effective wood cutting across different wood densities [27–30]. This method results in smoother surface finishes and reduces the risk of wood burning during high-speed operations.

One notable advantage is the compatibility with standard rotary tools and carving bits; however, the limitation lies in the increased cost and complexity of cooling or maintaining high-speed motors over prolonged use.

To tackle the issue of vibration and tool stability, methods such as using reinforced aluminium or steel frames and precision linear rails are employed [31–33]. These approaches help in distributing forces more evenly and minimizing structural deflection during carving. The results show improved carving accuracy and reduced tool wear. The advantage of this approach is a noticeable increase in the quality and detail of carvings, especially in high-speed or deep-cut scenarios. Nevertheless, this adds to the overall machine weight and cost, making it less suitable for portable or budget-friendly designs.

In terms of precision, stepper or servo motor control combined with microstepping drivers is widely used to enhance positioning accuracy [34–36]. These methods have shown excellent results in reproducing fine patterns and maintaining tight tolerances. A clear advantage is the ability to achieve high repeatability and intricate detail, which is essential for both professional and artistic applications. However, a limitation is the need for careful calibration and potential system instability if components are not properly aligned or tuned.

Finally, to address the issue of wood chip accumulation, solutions such as integrated dust collection systems or strategically positioned air vents are implemented. These help in maintaining a clean working area and prevent machine jamming. While this improves machine reliability and reduces downtime, the limitation is the added complexity in design and the need for regular maintenance of dust filters and collectors. Overall, while these methods collectively improve the performance and reliability of prototype wood carving machines, the key trade-offs remain between precision and cost, and performance and design simplicity. Continued research is needed to develop more compact, efficient, and affordable solutions for widespread use.

To overcome the aforementioned challenges, this paper proposes a simple and low-cost design solution that integrates both mechanical and control components in a practical and efficient manner. The mechanical structure is built using lightweight aluminum profiles, which are affordable, easy to assemble, and provide sufficient rigidity for wood carving tasks. This approach ensures that the final prototype is not only functional and accurate but also accessible for small workshops, hobbyists, and educational institutions with limited budgets.

3.Materials and methods

The design procedure can be summarized in the following steps:

- The 3D model is created using Unigraphics (NX) software.
- Finite element method is conducted to evaluate the structural durability of the 3D model.
- Standard components that are commercially available are selected.
- An appropriate control system is chosen.
- The prototype machine is fabricated based on the finalized design.

3.1Spindle motor selection

In CNC machines, selecting the right spindle motor is crucial as it directly impacts both the machine's performance and cost. Stepper motors typically do not provide the necessary torque and speed for the spindle, whereas both electric and servo motors can meet these requirements [37, 38]. However, electric motors offer significant advantages in terms of lower cost and simpler control systems compared to servo motors.

Depending on the material being processed, choosing an electric motor with the appropriate power can meet the cutting requirements while optimizing costs. For softer materials like wood, acrylic, and aluminium, a lower-power motor is usually sufficient. Based on the design requirements, the 775 DC motor with 80W power has been identified as a suitable choice for the spindle, being readily available and cost-effective as shown in *Figure 1*. Its specification is shown in *Table 1*.

Figure 1 Motor DC RS-775 80W

Table 1 RS-775 motor's specification

Specification	Value
Motor type	Brushed DC motor
Brushed DC motor	6V-38VDC
Speed	4000RPM-28000RPM
Torque	300g.cm-1300g.cm
Shaft diameter	5mm
Rotating direction	Clock wise – counter clock wise
Bearing	oil bearing

3.2Mechanical design for wood carving machine

Figure 2 illustrates the components of a mechanical structure with a simple design, consisting of 23 main parts. Each component is manufactured according to strict standards, utilizing hex screws, nuts, bolts, and aluminium profiles to ensure precision and durability. This section focuses on the detailed design of key components, emphasizing the fabrication and assembly processes to ensure structural stability and dimensional accuracy. The meticulous attention to each part plays a crucial role in optimizing the machine's performance and longevity.

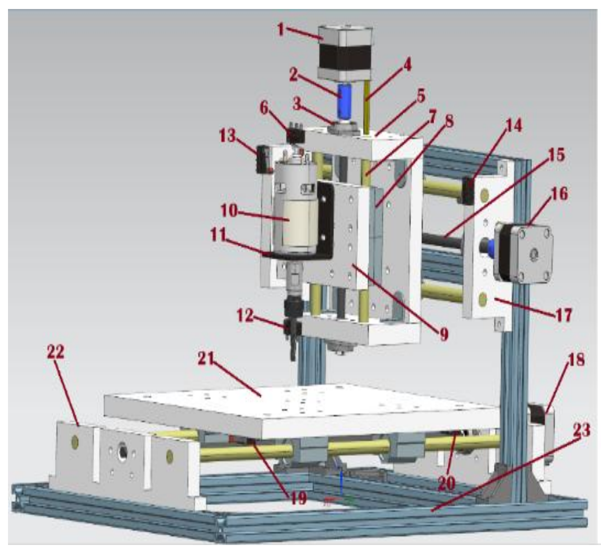


Figure 2 3D Model of the Small 3-Axis CNC Wood Engraving Machine: (1)Z-axis stepper motor, (2) Rigid couplings, (3) KFL08 ball screw supports, (4) M3-40 brass standoffs, (5) Z-axis column bracket, (6) Z++ axis limit switch, (7) 10mm round linear rail, (8) SCS10UU round linear slider, (9) Spindle mount, (10) 775 motor, (11)775 motor bracket, (12) Z- axis limit switch, (13) X- axis limit switch, (14) X++ axis limit switch, (15) T8 lead screw, (16) X-axis stepper motor, (17) X-axis bracket, (18) Y-axis stepper motor, (19) Y-axis limit switch, (20) Y++ axis limit switch, (21) Machine table, (22) Y-axis bracket, (23) Machine frame

3.2.1Machine frame

As shown in *Figure 3*, the CNC machine frame is constructed from 20×20 mm aluminium profiles, with the structure currently in the preliminary assembly phase. The frame is made up of aluminium profiles, connected at key points by metal corner brackets, which help enhance the strength and stability of the entire structure [39]. The design features two distinct levels, with a smaller structure at the top and a wider frame at the bottom. The use of metal corner brackets, combined with a system of screws and bolts, indicates that although the frame is not yet fully assembled, it has attained a fundamental level of stability, making it ready for the subsequent steps in the assembly process.

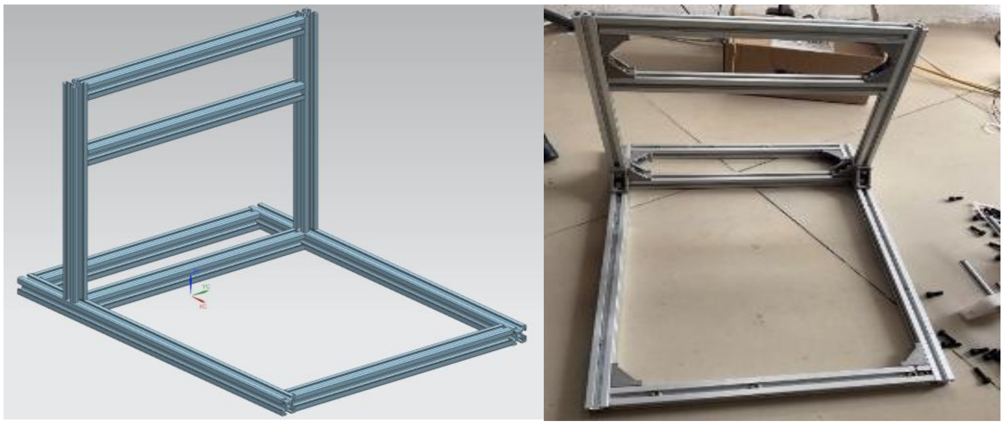


Figure 3 3D model and actual model of a CNC wood engraving frame

3.2.2Machine table

The machine table is constructed from 15 mm thick, high-durability polyoxymethylene (POM) plastic and is precisely shaped according to the 3D design illustrated in *Figure 4*. A CNC milling machine is employed to accurately mill the outer contours and mark the positions of the mounting holes on the table surface. Following this, a drilling machine with appropriately sized drill bits is used to bore through the marked holes. These holes serve a critical function, allowing for the attachment of round linear bearings, ball screw housings, and various fixtures, ensuring proper alignment and functionality of the machine components.

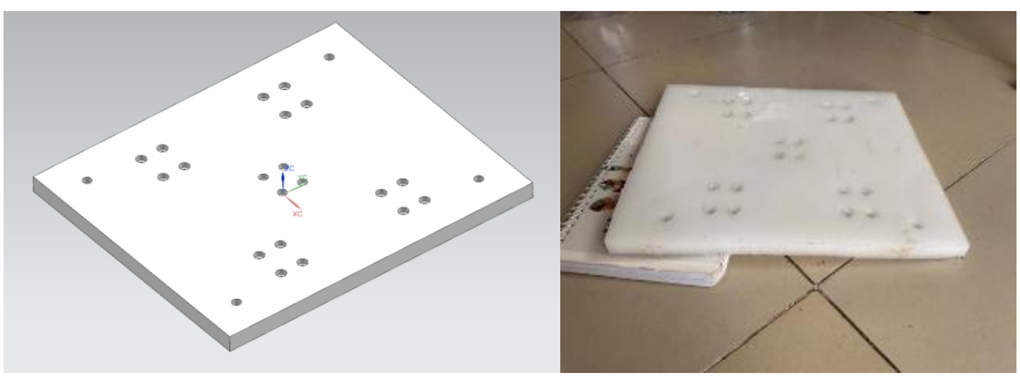


Figure 4 3D and actual fabrication of the machine table

3.3Calculating and selecting a ball screw

To calculate and select an appropriate ball screw for the system, several important steps must be followed, each accompanied by a key formula.

First, the axial force F_a acting on the ball screw is calculated using the formula given in Equation 1.

$$F_a = m.g \quad (1)$$

Where m is the mass in kilograms, and g is the acceleration due to gravity.

Equation 1 helps determine the weight load that the ball screw needs to support. Next, to ensure the ball screw can withstand the load without deforming, the average thread diameter d_2 must be calculated using the formula shown in Equation 2.

$$d_2 \geq \sqrt{\frac{F_a}{\pi.\Psi_h\Psi_H.[q]}} \quad (2)$$

Where Ψ_H represents the nut height coefficient, which accounts for the influence of the nut's height on the distribution of load across the threads, Ψ_h is the thread height coefficient, which reflects the geometry of the thread profile and how effectively it can engage with the mating thread to resist axial loads and [q] denotes the allowable pressure.

This helps define the proper thread size to ensure the strength of the ball screw. Then, to verify the strength of the ball screw, the Equation 3 is used.

$$\sigma_{td} = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{(\frac{4F_a}{\pi.{d_1}^2})^2 + 3(\frac{T}{0{,}2.{d_1}^3})^2} \leq [\sigma] \quad (3)$$

The Equation 3 is used to calculate the equivalent stress (also known as the Von Mises stress) in a material subjected to combined loading conditions. This expression is derived from the Von Mises yield criterion, which is commonly used in engineering to predict yielding of ductile materials under complex states of stress. σ_{td} is the equivalent or Von Mises Stress, σ is the normal stress and τ represents the shear stress. The given formula represents the von Mises equivalent stress used to evaluate the mechanical strength of a circular shaft subjected to combined loading—specifically, an axial force Fa and a torque T. This criterion is based on the distortion energy theory, which is commonly applied in the design of mechanical components made from ductile materials. The objective of the formula is to calculate an equivalent stress, σ_{td}, that accounts for both the normal stress caused by the axial force and the shear stress induced by the applied torque. This equivalent stress is then compared to the allowable stress [σ] which represents the maximum stress the material can safely withstand.

This Equation 4 ensures the ball screw can handle the stress applied to it without exceeding the material's allowable stress limits. Afterward, the required torque Tr to move the axial load is calculated using the formula:

$$Tr = F_a.tan.(\gamma + \varphi).\frac{d_2}{2} \quad (4)$$

Equation 4 is used to calculate the torque required to rotate a screw under axial load F_a, taking into account both the thread geometry and friction effects. This is especially relevant in power screws or lead screws, where torque is needed to overcome both the thread's helix angle and friction. This ensures that the drive system has enough torque to move the load along the axis. The angle γ denotes the lead angle of the thread, which describes the steepness of the thread's helical path. The angle φ is the friction angle, The diameter d/2 refers to the pitch diameter of the thread, which is the effective diameter at which force is transmitted.

Next, the moment of inertia J of the ball screw is determined to ensure it can resist bending under load (Equation 5).

$$J = \frac{\pi.{d_1}^2}{4}(0{,}4 + 0{,}6.\frac{d}{d1}) \quad (5)$$

In Equation 5, J denotes the polar moment of inertia, which is critical for determining the thread's resistance to shear stress. The parameter d_1 refers to the minor diameter of the internal thread, representing the smallest diameter measured at the root of the threads. In contrast, d represents the major diameter, which is the largest diameter of the external thread profile.

The slenderness ratio λ is calculated to check the rigidity of the ball screw, preventing excessive bending under load (Equation 6).

$$\lambda = \frac{\mu.l}{i} \quad (6)$$

In Equation 6, λ is a dimensionless parameter that typically characterizes the system's frictional resistance or efficiency factor. The symbol μ denotes the coefficient of friction between the mating surfaces, such as the threads of a screw and a nut. The variable l refers to the lead of the screw, which is the axial distance the nut advances with one full revolution. Lastly, i represent the mechanical advantage or transmission ratio, indicating how rotational input is converted into linear motion.

Finally, the critical load F_{th} is calculated using Euler's formula, which determines whether the ball screw can withstand the load without losing stability (Equation 7).

$$F_{th} = \pi^2.E.\frac{J}{(\mu.l)^2} \quad (7)$$

In Equation 7, F_{th} represents the theoretical or critical force at which the system may become unstable or buckle. Meanwhile, μ is the coefficient of friction between the threaded surfaces, and l is the lead of the screw, representing the axial distance moved per revolution.

Based on the results of all calculations, the D8 ball screw with an 8 mm lead is identified as the optimal choice. It offers the required strength, load capacity, and structural stability, while satisfying all technical and operational specifications of the system.

3.4Strength testing

After designing and manufacturing the components of the small wood engraving machine, the next phase involved assembly and durability testing [40]. The first step in the durability analysis was the careful selection of appropriate materials for each component. The machine frame is constructed from 6061 aluminium, a strong and lightweight material that ensures structural stability. The machine table and support shafts are made of POM, a plastic known for its good mechanical strength and wear resistance, making it suitable for medium-load applications. Components such as linear bearings and ball screw nuts are fabricated from 5086 aluminium, a hard aluminium alloy that provides excellent precision and load-bearing capabilities.

Lastly, the round guide rails and ball screws are made from hardened steel, offering high hardness and accuracy in linear motion.

The machine's legs are considered fixed supports, meaning they are firmly attached to the ground, preventing any movement or deformation at these points, thus ensuring the system's stability. The total mass of the wood engraving machine was determined through Unigraphics (NX software) to be 8.1 kg [41]. Based on this mass, the distributed force acting on the machine's lower frame was calculated and set to 100 N to ensure accurate and safe calculations.

The mass of the machine table, along with other components like the workpiece and fixtures, is calculated to be 3 kg, generating a distributed force on the machine table. This force was chosen to be 30 N to ensure the system's safety during operation. The Z-axis of the machine weighs 2.5 kg, creating a distributed force on the Z-axis, with the force set at 25 N. Additionally, when the spindle motor operates, it generates a torque acting on the motor shaft with a value of 0.79 N.m (equivalent to 790 N.mm). This is crucial to ensure that the motor shaft can withstand the torsional load without deformation or failure. The processes described above are illustrated in *Figure 5*.

The displacement results, calculated using NX software and illustrated in *Figure 6(a)*, show that the maximum displacement occurs along the X-axis, with a value of 0.1042 mm. This small displacement indicates that the system exhibits high rigidity and structural stability under the applied loads. The minimal deformation ensures that the precision of the wood engraving process is maintained, preventing any significant deviations during operation.

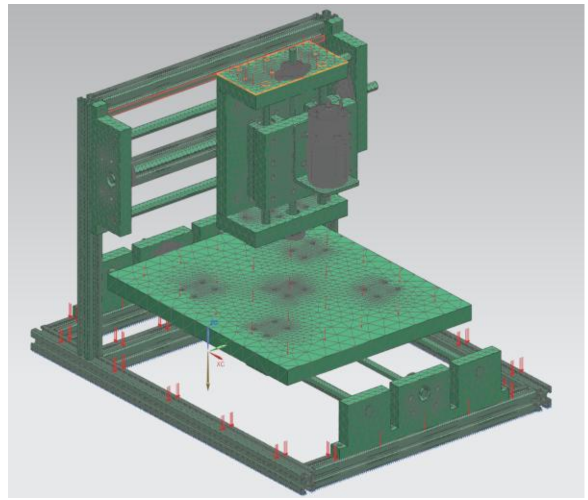
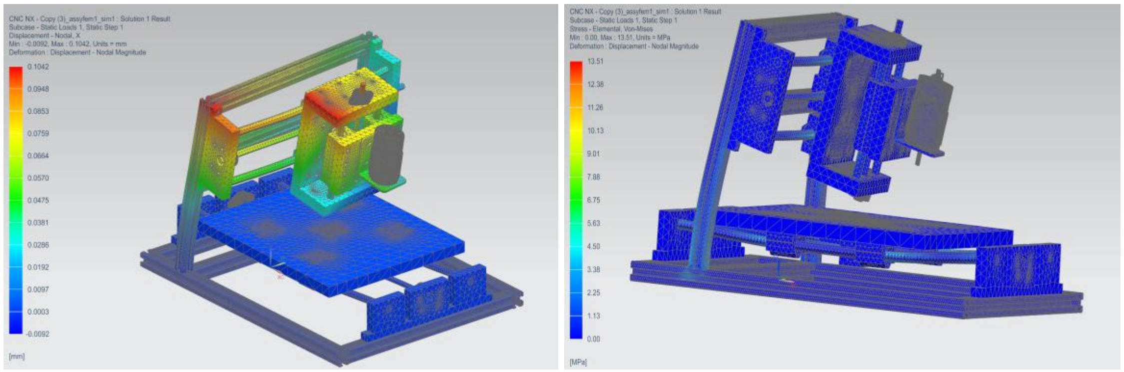


Figure 5 Apply distributed load to the machine

Regarding stress analysis in *Figure 6(b)*, the yield strength of 6061 aluminium, which is used for the machine frame, is 276 MPa, while the yield strength of POM, used for the machine table and supports, is 82.7 MPa [42–44]. The maximum stress calculated in the NX simulation is 13.51 MPa, which is significantly lower than the yield strength of both materials. This indicates that the applied loads remain well below the material limits, ensuring that neither the aluminum nor the POM components undergo permanent deformation under the current load conditions.

Based on the stress and displacement results, the CNC wood engraving machine can fully meet the design requirements. The small displacement and low stress levels demonstrate that the system is structurally sound and can withstand operational forces without compromising safety or performance. The materials chosen, including aluminium and POM, provide the necessary strength and durability for long-term operation, ensuring that the machine remains reliable and functional under expected workloads.



(a) (b)

Figure 6 Strength analysis results for the system a) Displacement results in the X direction, b) Stress

3.5Control software

After calculating the required torque for the X, Y, and Z axes, the KH42JM stepper motor and TB6600 motor driver were selected. Their specifications are presented in *Table 2* and *Table 3*, respectively. *Figure 7* shows the control circuit wiring diagram of the machine and its actual image of the electrical circuit board.

Table 2 Stepper motor KH42 JM specification

Specification	Value
Drive method	Uni polar
Number of phases	2
Voltage	3.06 V
Current	0.9 A/phase
Holding torque	140 mN.m
Detent torque	11.4 mN.m
Rotor inertia	38g.cm^2

Table 3 Stepper motor KH42 JM specification

Specification	Value
Power Supply	V - 50V DC
Output current	0.3 A - 4.5 A
Micro Step	1.. 2 .. 8 .. 16
Maximum PWM frequency	200 kHz
Hold Current Adjustment	50% or 100%.

Mach3 CNC software is a versatile and flexible tool for controlling various types of CNC machines, including mini wood engraving machines [39,40,45]. The main interface of Mach3 includes six screens for functions such as program control, numerical control (NC) command input, toolpath setup, coordinate system configuration, and system diagnostics as shown in *Figure 8.*

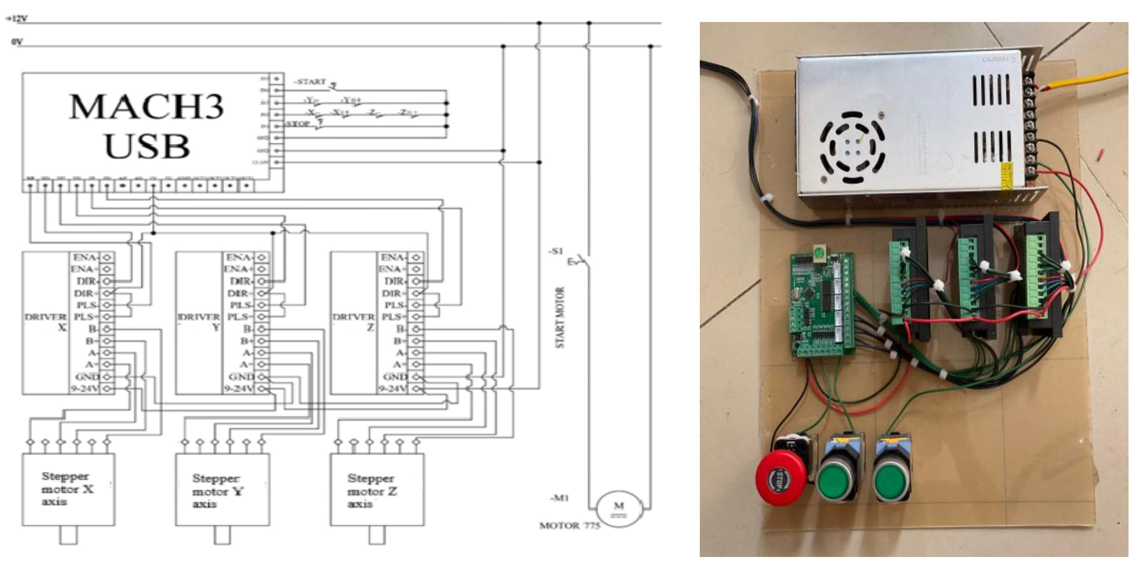


Figure 7 Circuit wiring diagram (left) and actual circuit board (right)

Users can configure the motors for the X, Y, and Z axes by selecting Config, Ports and Pins, Motor Outputs and set control parameters like step size, velocity, and acceleration in Motor Tuning. The number of pulses required to move 1 mm is calculated, and for the mini wood engraving machine, this value is 400 pulses/mm.

The software also allows users to set travel limits and the home position by configuring input pins connected to limit switches, ensuring the axes operate within safe boundaries. Mach3 provides precise and stable control for mini wood engraving machines during operation.

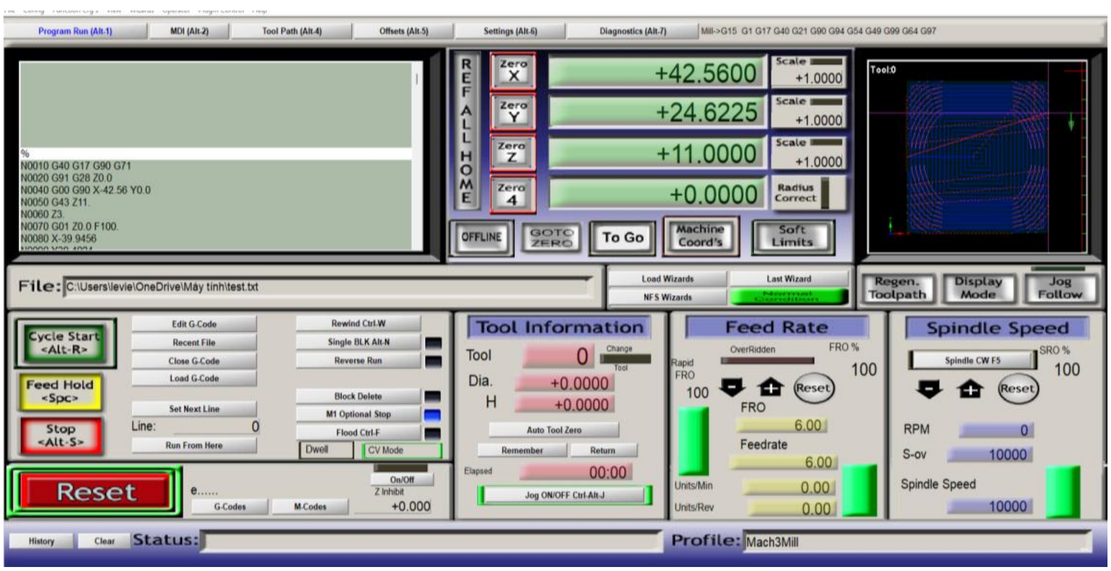


Figure 8 Main interface of the Mach3 software

4.Results

After completing the design, machining the components, and integrating the control system, the final step involves assembling and finalizing the 3-axis mini-CNC wood engraving machine, as illustrated in *Figure* 9. The majority of the machine components utilize readily available standard parts, such as aluminium extrusion profiles, linear rails, lead screws, and NEMA 17 stepper motors. This choice reduces sourcing complexity and facilitates easy replacement or future upgrades.

A limited number of components, including the spindle stand and machine table, are 3D printed using polylactic acid (PLA) material. PLA is selected for its low cost, ease of customization, and suitability for non-load-bearing applications. The aluminium frame is cut with a tolerance of ±0.5 mm to ensure squareness and structural rigidity, while guide rails and motor mounts are assembled using pre-drilled holes with a ±0.2 mm tolerance to maintain precise linear motion. The 3D printed parts are designed with a ±0.1 mm fit to provide stable support for both the spindle and the work surface.

This hybrid approach—combining standard hardware with selectively 3D-printed parts—streamlines the manufacturing process and enables rapid prototyping and personalization. The result is a lightweight, compact, and cost-effective machine that can be assembled with basic tools and operated using open-source control software for precise wood carving. The specifications of the prototype are summarized in *Table 4.*

Table 4 Prototype machine's specification

Specification	Value
Number of axis	3
Dimension	800×600×620 mm
Maximum feed rate	12 m/min
Recommend feed rate	300-670 mm/min
Spindle speed	50-12000 rpm
Control software	Mach 3

The machine axes align is checked by using a Mitutoyo dial indicator with resolution of 0.01 mm. The checking steps are follows:

- The dial indicator is sticked to the main spindle.
- The probe is touched the face and the X and Y side edges of the machine table
- The indicator is set to 0.

- Using jog mode in Mach 3 controller.
- Move along the axis to check to square and aligned of the machine axes.

The machine axes are calibrated using a micrometre with 0.02 mm resolution. This involves measuring the actual travel distance of the machine along each axis and verifying that it meets the design requirement. The results shown in *Figure 10* of the wood engraving machine demonstrate a high level of precision in creating intricate details. The feed rate of the experiment is at 500 mm/min with the spindle speed at 8000 rpm. The outlines of the patterns and letters are sharp, reflecting excellent control over the axes and cutting tools. The accuracy of the products is ±0.5 mm, which is acceptable. This level of precision is sufficient for decorative patterns, text engraving, and small reliefs where high artistic detail is needed but ultra-fine resolution is not critical. The tolerance was assessed by comparing key reference dimensions in the carved output—such as the width of lines, spacing between features, and depth consistency—to the original design file using digital calipers. The machine handles a range of designs, from simple shapes like flowers and letters to more complex figures such as dragons and human silhouettes, showcasing its versatility in engraving various models. Additionally, the outer edges of the circles are cleanly cut with no signs of chipping, highlighting the machine's capability for precise edge cutting. Overall, while the mini wood engraving machine performs effectively, improving the surface smoothness would lead to a more polished and professional result.

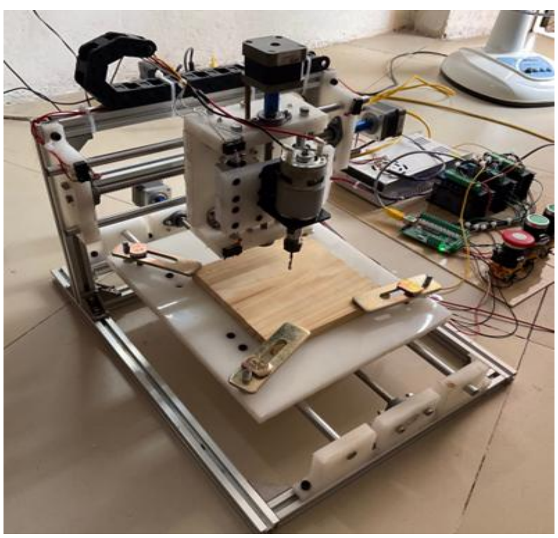


Figure 9 The completed 3-axis CNC wood engraving machine after full assembly

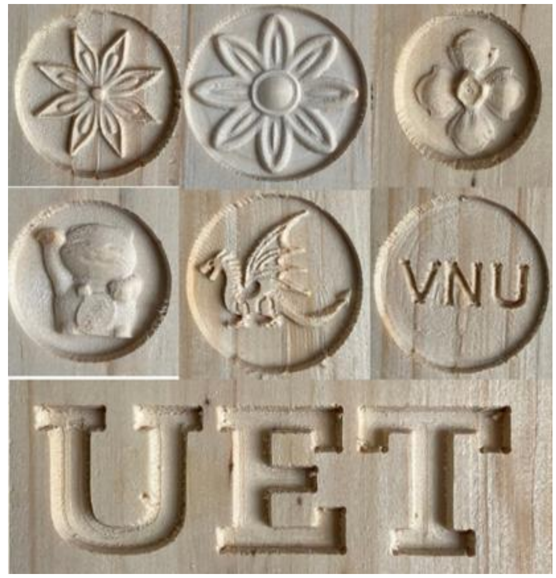


Figure 10 Sample engraved products created using the 3-axis CNC wood engraving machine

5.Discussion

Due to its open-frame design, the machine generates a significant amount of wood chip dispersion, resulting in a relatively messy work environment. The machine frame, constructed from aluminum for cost-effectiveness, lacks optimal structural rigidity. As a result, when the spindle operates at speeds exceeding 10,000 rpm, noticeable vibrations occur, leading to reduced accuracy.

Experimental results indicate a cutting accuracy of approximately ±0.5 mm. However, certain surface finishes appear slightly rough, likely due to large step sizes or unoptimized cutting speeds. These issues could be mitigated by refining the speed and step parameters. Despite these limitations, the engraved depth remains consistent, demonstrating effective Z-axis control and precision.

It is also noted that the current design does not yet address environmental considerations or incorporate essential safety features, which should be factored into future design iterations.

Furthermore, the machine demonstrates significant cost-effectiveness when compared to other commercial products such as the Shapeoko 5 Pro, X-Carve Pro CNC, and 3018 CNC, as detailed in *Table 5*. Its simplicity in both maintenance and assembly enhances its suitability for local use, aligning well with the prevailing economic conditions in Vietnam.

Table 5 Price comparison of proposed machine with commercial products

Wood carving machine	Price (USD)	Max feed rate (mm/min)	Software compatibility
Proposed machine	216	1000	Open source
Shapeoko 5 Pro [46, 47]	3200	3000	Carbide Create, Fusion 360
X carve pro CNC [48, 49]	4250	2000	Easel, Fusion 360
3018 CNC [50, 51]	344.09	800	Software Compatibility

The prototype CNC wood carving machine is significantly more affordable than commercial models such as the Shapeoko and X-Carve, and its cost is comparable to that of the 3018 CNC. While offering better rigidity and faster operation than typical entry-level 3018 machines with similar build volumes, it falls slightly short in terms of precision. Nonetheless, the prototype provides a budget-friendly and functional entry point into CNC wood carving, making it well-suited for hobbyists, students, and small-scale project makers.

The development of this prototype demonstrates that it is feasible to construct a low-cost yet functional CNC machine primarily using standard components, supplemented with a few 3D-printed parts. The machine achieved a positioning accuracy of approximately ±0.5 mm and a maximum feed rate of 1000 mm/min. It successfully carved softwoods and Medium-density fibreboard (MDF), delivering acceptable surface finishes and reliable repeatability. These results validate the design approach, which prioritizes affordability, ease of assembly, and user accessibility through the use of open-source hardware and software.

From a performance perspective, the prototype meets its intended objectives for small-scale and hobbyist applications. The frame, built from 20×20 mm aluminium extrusions, provides adequate rigidity, while the use of stepper motors and an Arduino-based GRBL control system enables consistent and reliable axis movement. However, certain performance aspects—including carving precision, vibration suppression, and compatibility with harder materials—highlight areas for future improvement, particularly when the machine is used for deeper cuts or more demanding applications.

Although the machine frame is constructed from aluminum for affordability and ease of assembly, this material choice limits the structural rigidity of the system. This indicates that while the design is lightweight and economical, it may not be suitable for high-speed or precision-intensive operations without further structural optimization. The machine's open-frame design leads to significant wood chip dispersion, creating a messy and potentially hazardous working environment. Furthermore, essential safety features such as spindle covers, dust enclosures, and emergency shut-off mechanisms are not yet incorporated, which could limit its usability in public or educational settings where safety regulations are strict.

A complete list of abbreviations is listed in *Appendix I*.

6.Conclusion and future work

The results of this study demonstrate that the small 3-axis CNC wood carving machine effectively meets the design and operational objectives outlined in this work. The machine exhibits a high level of precision in producing intricate details, as evidenced by the clear and sharp outlines of engraved patterns and letters. The consistent engraving depth confirms precise Z-axis control, and the system successfully handles a wide range of designs, from simple geometries to complex figures.

The machine delivers efficient performance, achieving clean edge cuts with minimal error rates. However, some surface roughness was observed, likely due to relatively large step sizes or unoptimized cutting speeds—factors that can be improved through parameter tuning. Despite these minor issues, the study validates that the machine enhances the quality of wood products by maintaining precision and aligns with industry trends toward automation and digital manufacturing.

In terms of functionality, the prototype proves to be versatile, capable of carving, milling, and drilling on various materials such as wood, mica, and aluminum. Its cost-effectiveness, ease of maintenance, and reduced labor and production time make it particularly well-suited for small-scale woodworking applications, especially within Vietnam's wood processing sector.

The structural analysis conducted using NX software validated the prototype's mechanical integrity and indicated readiness for further refinement through topology optimization. Based on these findings, several opportunities for future improvements have been identified:

- Structural optimization of the machine to improve rigidity and reduce vibration.
- Design enhancements to improve operational safety, such as implementing covers for ball screws and integrating a spindle-mounted dust collection system.
- Material upgrades, including the use of sturdier materials for the machine frame and work table to further suppress vibration and improve performance during high-speed operation.

Acknowledgment
None.

Conflicts of interest
The authors have no conflicts of interest to declare.

Data availability
The data may be provided by the corresponding author upon reasonable request.

Authors contribution statement
Tran Thanh Tung: Writing, software, original draft preparation, investigation, experiment, manufacturing, design, software and simulation. **Nguyen Thi Anh:** Writing, design, software and simulation. **Tran Vu Minh:** Conceptualization, methodology, supervision, reviewing and editing.

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Appendix I

S. No.	Abbreviation	Description
1	CAD	Computer Aided Design
2	CAM	Computer Aided Manufacturing
3	CNC	Computer Numerical Control
4	MDF	Medium-Density Fibreboard
5	NC	Numerical Control
6	PLA	Polylactic Acid
7	TCM	Tool Condition Monitoring
8	Unigraphics	NX software
9	3D	Three-Dimensional