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# Design and Fabrication of a Low-Cost 3-Axis CNC Milling Machine for Small Enterprises

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**Abstract:**
The high price and low accessibility of commercial 3-axis CNC milling machines is a challenge that many small businesses and educational establishments face. Consequently, affordable and accessible CNC machines that offer reliable machining are needed in training and light production. This work explores the design, implementation, and performance assessment of a compact low-cost 3-axis CNC machine for small enterprise and academic applications. The machine utilizes an aluminum frame, lead screws with anti-backlash nuts, linear guides and NEMA 17 stepper motors to drive the X, Y and Z axes. Control system implemented on Arduino Uno operated via GRBL firmware performs the task of carrying out G-code operations, controlled through open-source CNC software. The CNC prototype was developed and calibrated for the evaluation of kinematic accuracy and operational performance. Observations from experiments show axis positioning precision in the range of ±0.05–0.10 mm and maintaining repeatability up to ±0.05 mm. Machining trials on wood, aluminum and acrylic exhibit dependable multi-material cutting capabilities resulting in a smooth and consistent surface. The CNC machine, with an approximate cost of 450 USD, provides a cost-effective alternative to commercial CNC machines for prototyping, training, and light manufacturing applications.

**Keywords:** CNC Milling Machine, Small Enterprise, Arduino Uno, Stepper Motor, G-Code, Machining Trials, Low-Cost

## Introduction
CNC milling machines are extensively used for high precision manufacturing owing to their capability to generate complex geometries with high dimensional accuracy and repeatability. They are indispensable in several industries such as aerospace, automotive, and electronics, where high-accuracy tolerances and high-quality surface consistency are needed [1–4]. Commercial CNC systems are however costly, need expert operation, and their servicing is intricate which restricts accessibility to small enterprises, learning institutions and low-budget prototyping labs [5–7].
In order to overcome these setbacks, more recent studies have concentrated on low-priced CNC platforms, which rely on open-source equipment, stepper motors, and modular mechanical structures. These systems prove that acceptable accuracy can be realized at much less cost [8–12]. Most of the reported designs, though, are characterized by a low degree of structural rigidity, low positional precision and low machinability in multiple materials which limits their usability into practice [12,13].
This research paper contains the design, production, and experimental testing of a low-cost three-axis CNC milling machine that can be used in small-scale production, educational prototype, and

light-duty machining. The suggested system incorporates a modular mechanical design, linear motion lead screw driven, and open-source controller system based on the Arduino platform. The goal will be to have an affordable yet precise and flexible operational mix that meets the needs of a scholarly and small business setting. The purpose is to accomplish a balanced trade-off in affordability, dimensional accuracy and operational adaptability applicable in academic settings and small-scale industrial environments.

## Literature Review

CNC technology has transformed remarkably throughout the last decades, allowing exceptionally precise and reproducible manufacturing operations [2,14,15]. Industrial CNC machines have high-performance but are linked to high cost, complexity of the system, and skilled labor, which limit them to use in small businesses and educational institutions [11,16,17].

A number of studies have attempted to develop low-cost CNC machines in a bid to overcome the shortcomings of high-priced industrial systems [18,19]. Previous studies have established that it is possible to design compact 3-axis CNC milling machines capable of machining wood and soft metals at an acceptable level of accuracy at a lower cost [18,20–22]. CNC routers have also been investigated in other studies, focusing on wood engraving applications, with stepper motor operated axes and inexpensive open-source control electronics [23–25]. CNC machines on a laboratory scale-including modular mechanical architecture have also been reported, specifically in education, where simple assembly, customization, and maintenance are deemed key concepts [26–28]. All these studies have shown that low-cost desktop CNC systems could be functional enough to perform prototyping, training, and light-duty machining.

Open-source electronics and software have also helped in lowering the cost of the system and raising design flexibility. Motion control has been commonly performed using Arduino-based controllers and G-code interpreters in inexpensive CNC machines [8,29,30]. In spite of such developments, frame rigidity, backlash, vibration, and lack of machining capability remain an issue in many reported systems when handling various materials [31–33].

According to the literature reviewed, there is still a gap in the realization of a low-cost CNC milling machine with a combination of a strong mechanical design, a reliable multi-axis control, and full open-source hardware and software compatibility. The current research fills this gap by designing, manufacturing, and testing a 3-axis CNC milling machine that is applicable in small-scale productions, education prototyping, and machining of multi-materials.

## Methodology

The approach to the design of the 3-axis CNC milling machine is broken down into design and CAD modelling, mechanical and electronic manufacturing, software process, and testing and validation. The design is translated into physical motion by the system through synchronization of stepper motors and lead screws by using an Arduino-based control.

## Design Overview

The proposed CNC milling machine is a low-cost 3-axis (X, Y, Z) modular design that can be easily used and fabricated. The design emphasizes dimensional accuracy, structural reliability and compatibility with open-source electronic platforms. The frame is made of aluminum extrusion profiles, which give lightweight rigidity and the linear movement along each axis is enabled by lead screws and linear guide rails. The three axes are powered by stepper motors and microstepping is used in order to enhance motion resolution and positional accuracy.

Figure 1 shows structural model (3D) of the positioning of the guide rods and the main support frame of the 3-axis milling system. Figure 2 gives a high-fidelity representation of the metallic frame assembly, a view of the worktable and gantry plate. The 3D CAD model of the assembled

3-axis CNC milling machine includes all four parts (X, Y, and Z-axis assemblies) of the machine, the frame structure, the linear guides, and the integrated spindle unit, as seen in figure 3. All these visualizations ensure the space arrangement, design, and movement directions of the offered machine, which can confirm the clear idea of components joining and functional organization.

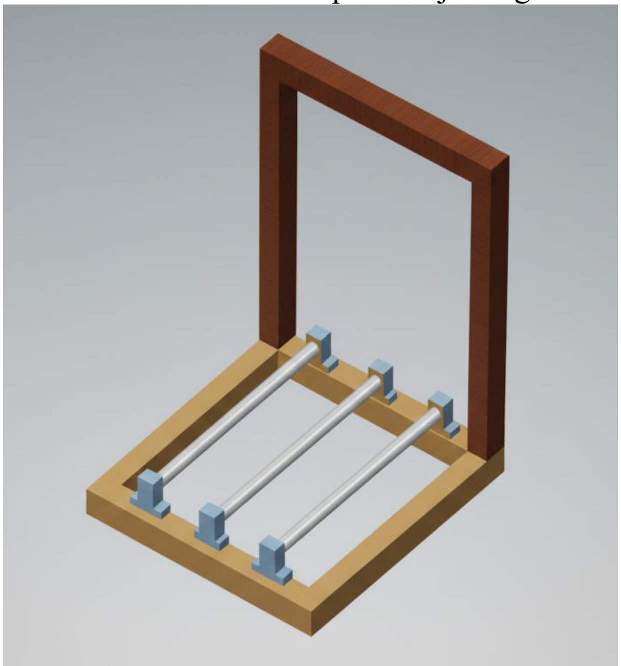

**Figure 1.** 3D structural model showcasing the arrangement of the guide rods and the primary support frame for the 3-axis milling system

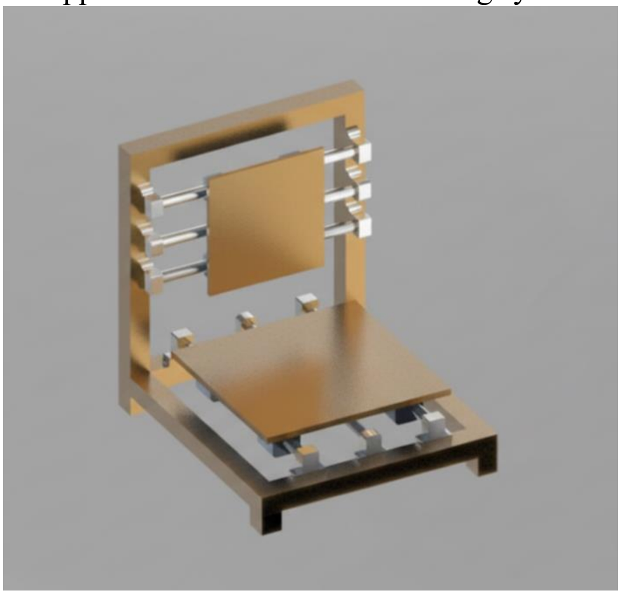

**Figure 2.** High-fidelity rendering of the metallic frame assembly, illustrating the worktable and gantry plate configuration.

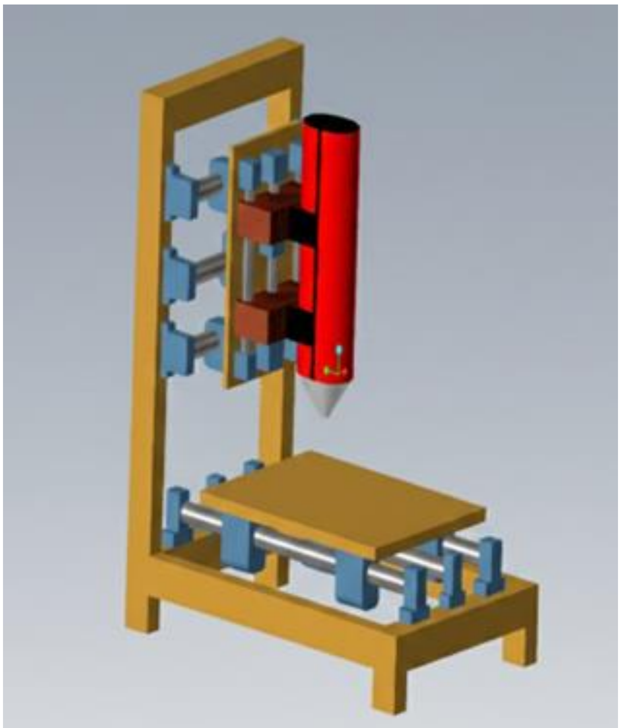

**Figure 3.** 3D CAD model of the complete 3-axis CNC milling machine, illustrating the X, Y, and Z-axis assemblies, frame structure, linear guides, and integrated spindle unit.

**Mechanical Components**

The mechanical structure of the system was designed in such a way that it would provide adequate rigidity, accuracy and be cost-effective. The frame itself is made of aluminum extrusion profiles and connected with the rest of the frame using standard brackets and fasteners. This design offers sufficient structural stability with a lightweight design that becomes easy to fabricate and assemble. Linear movements in the X, Y and Z directions are made possible by lead screws mounted on linear guide rails. Lead screws employ anti-backlash nuts to improve positioning accuracy and ensure consistent performance during machine operation. Linear guides provide a smooth movement and allow the transfer of the structural loads off the lead screws improving overall motion accuracy. NEMA 17 stepper motors are used in motion actuation. X and Y axes are powered via timing pulse systems, but the Z-axis is powered via its own dedicated stepper motor directly linked to a high precision lead screw. The material removal is accomplished with a low-cost DC spindle motor with 12 to 24 V range of operation with variable speed control that is appropriate in machining wood, plastics and soft metals. Figure 3 shows an exploded-view CAD model of the mechanical assembly, displaying frame arrangement, linear motion, location of stepper motors, and the combination of the spindle. The main specifications of the mechanical components such as dimensions, materials, motor ratings, spindle speed range and axis travel limits are summarized in Table 1.

**Table 1. Key specifications of the mechanical components**

| Component | Specification / Rating |
|---|---|
| Frame | Aluminum extrusion profiles, 40×40 mm cross-section, modular assembly with brackets and fasteners |
| X-axis Travel | 300 mm |
| Y-axis Travel | 200 mm |
| Z-axis Travel | 100 mm |

| Component | Specification / Rating |
|---|---|
| Lead Screws | 8 mm diameter, 2 mm lead, anti-backlash nuts |
| Linear Guides | 12 mm width, supported on all axes |
| Stepper Motors | NEMA 17, 1.8° step angle, 2 A rated, microstepping enabled |
| Spindle Motor | DC 12–24 V, 5000–12,000 rpm, variable speed control |
| Worktable | 300×200 mm, aluminum plate |

**Electronic and Control System**

The proposed 3-axis CNC milling machine has a control system that incorporates the open-source electronics to provide accurate motion control and flexibility of operation. The system focuses on Arduino Uno microcontroller that is used to communicate with A4988 stepper motor drivers to control the movement of all three axes. Step and direction signals are provided by the Arduino to the drivers to ensure precise motion of the NEMA 17 stepper motors along the three cartesian axes.

The open-source GRBL firmware controls toolpath execution, reads and executes standard G-code commands and converts them into precise multi-axis movements. A computer-based graphical user interface (GUI) enables the user to import G-code files, set cutting parameters, including feed rate and spindle speed, and observe real-time positional information along the respective axes. End-stop switches are fitted on each axis to guarantee safe and proper functioning. These sensors offer homing and limit sensing, allowing the machine not to cross its mechanical travel limits.

Wiring and interconnections within the system are presented in Figure 4, highlighting the Arduino Uno, stepper drivers, motors, power supply, and end-stop sensors. Table 2 gives the summary of the specifications of the electronic components in terms of voltages, currents, and functional purposes.

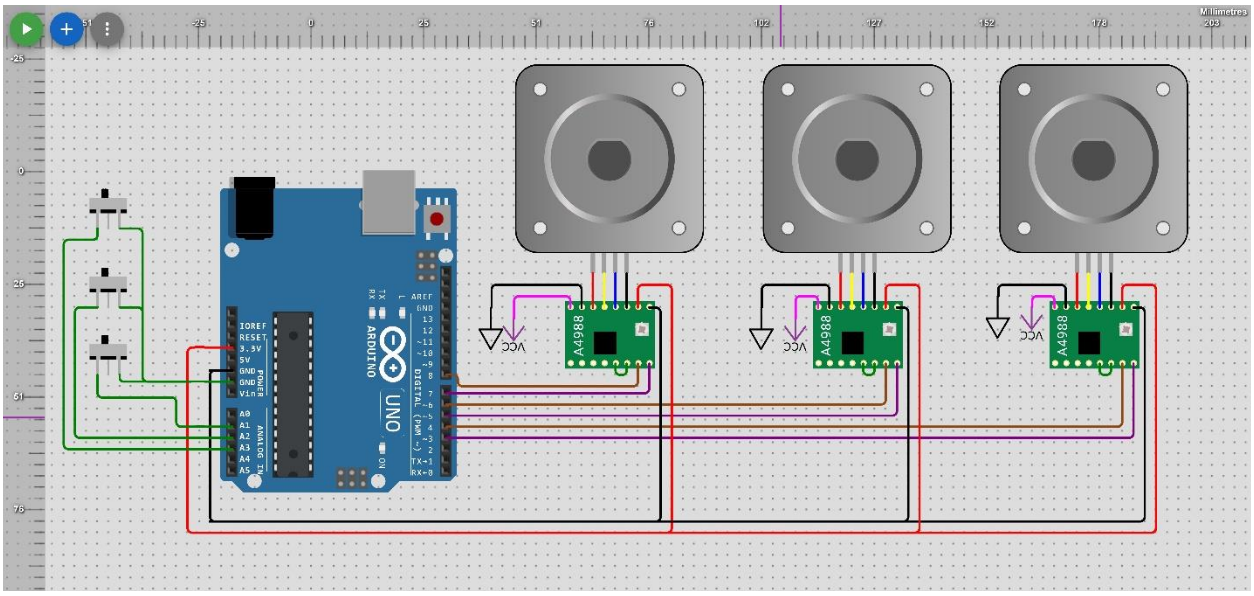


**Figure 4.** Wiring diagram showing Arduino Uno, A4988 stepper drivers, NEMA 17 stepper motors, power supply, and end-stop sensors for the 3-axis CNC milling machine.

**Table 2. Key specifications of electronic components**

| Component | Specification / Rating |
|---|---|
| Arduino Uno | ATmega328P, 16 MHz, 5 V logic, 14 digital I/O pins |
| Stepper Motor Driver | A4988, microstepping up to 1/16, 8 V–35 V input, 2 A max |
| Stepper Motors | NEMA 17, 1.8° step angle, 2 A rated, bipolar |
| Power Supply (X/Y) | 24 V, 3 A SMPS |
| Power Supply (Z) | 24 V, 3 A SMPS |
| Power Supply (Arduino) | 12 V, 1 A SMPS |
| End-stop Sensors | Mechanical limit switches, normally closed, for all axes |
| Software | GRBL firmware on Arduino, PC GUI for G-code execution |

**Fabrication and Assembly**

All mechanical elements were produced via conventional machining and processing techniques to guarantee dimensional precision and consistency. The main frame was made of aluminum extrusion profiles that were cut to lengths and joined together by the use of brackets and fasteners. Linear guide rails and lead screws were fitted with the aid of precision alignment jigs to reduce angular and parallel misalignment, which is very imperative in achieving smooth movement and positional accuracy.

The electronic parts were fitted in a modular wiring pattern. To guarantee an electrical safety level and easy maintenance, the Arduino-based controller, stepper motor drivers, and power supply units were enclosed in a protective enclosure. Wiring connections were systematically arranged to suppress electrical interference and troubleshooting.

System integration entailed installation of firmware and optimization of motion parameters. Steps per millimeter for each axis were set through regulated motion trials, and homing routines were evaluated by means of end-stop switches to guarantee uniform and repeatable reference positions. Figure 5 indicates the complete CNC milling machine connected to a computer with Candle software and thus the integrated mechanical and electronic system is ready to operate. These operations were used to guarantee multi-axis movement and consistency of machine operation.

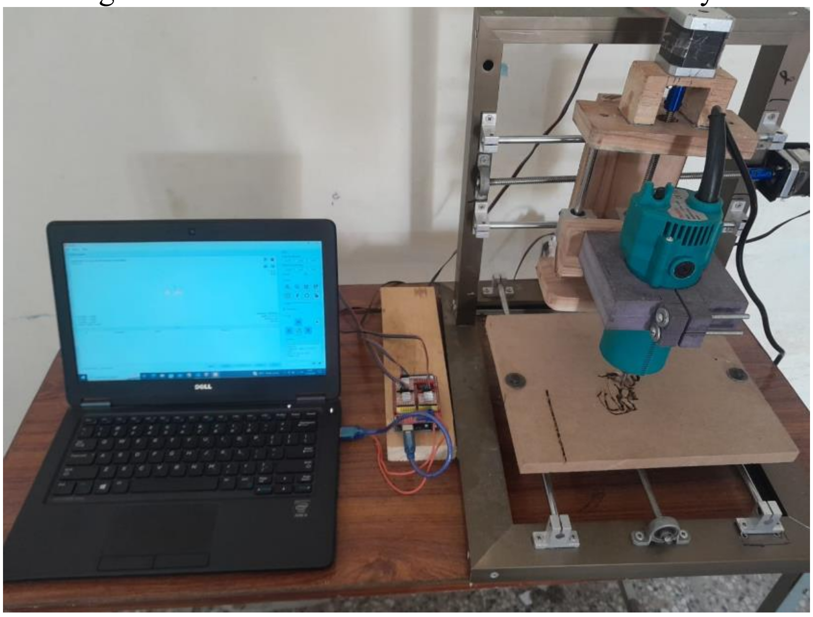

**Figure 5.** Fully assembled 3-axis CNC milling machine with Arduino-based control system connected to a computer for real-time G-code execution.

**Software Workflow**

The software workflow provides the ability to export a 3D CAD design into a machined component by means of a sequential digital-to-physical conversion. First, standard CAD software is used to design components and then they are exported in the STL format. The generated STL files are subsequently displayed in CAM software, which is then implemented to generate machine-readable G-code from the files defining toolpaths, feed rates, spindle speeds, and other machining parameters. The resulting G-code is sent to the Arduino controller through Candle software that provides an interface to the GRBL firmware that runs on the microcontroller. These commands are interpreted by the firmware and the stepper motors are moved along the X, Y and Z axes to replicate the geometry initially intended with great precision. The graphical user interface permits live monitoring along the axes and implementation of tool paths. The general steps and information chain are depicted in Figure 6, which depicts how the CAD, CAM, G-code generation, and coordinated motion control through GRBL and Candle interface are combined.

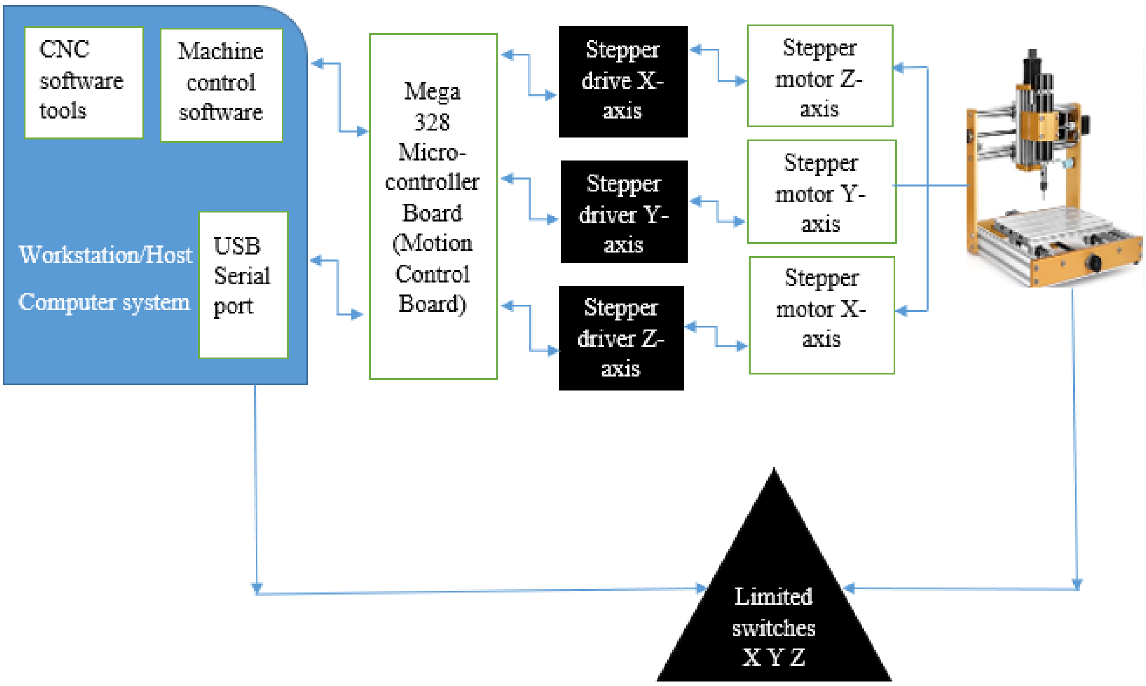


**Figure 6.** The integrated software toolchain and data flow diagram, illustrating the conversion of CAD geometries into machine-readable G-code and the subsequent real-time motion synchronization via GRBL firmware and the Candle GUI.

**Testing and Validation**

The assembled CNC milling machine was tested in a systematic manner in order to examine positional accuracy, repeatability, and milling performance.

**Positional Accuracy and Repeatability:**

All three axes (X, Y, Z) were checked in terms of positional accuracy through dial indicators and micrometers on the repetitive travel distances. The machine was moved into the predetermined positions repeatedly and the differences between the nominal positions and the actual positions were noted. Repeatability was calculated by getting the difference in position after ten repetitive cycles. Table 3 illustrates that the X-axis, Y-axis, and Z-axis had an average deviation of 0.08 mm, 0.10 mm and 0.06 mm respectively and the repeatability was ±0.05 mm across the three axes. These findings suggest that the machine is reliable in positioning that can be used in small-scale manufacturing and prototyping. The main causes of minor deviations were lead screw backlash and frame compliance.

**Milling Performance:**

Pinewood, acrylic and 6061 aluminum sheets were milled to test surface finish, dimensional accuracy and vibration behavior. Material parameters were adjusted across varying feed rates and spindle rotational speeds. Table 4 indicated that pinewood and acrylic had relatively smooth surface finishes with little or no tool marks whereas aluminum was relatively rougher along the surface because of slight vibrations at higher feed rates. The testing did not show any stepper motor skipping or G-code execution errors.

Observations during milling included:

- Reliable axis movement and low vibrational response for wooden and acrylic materials
- Stable dimensional accuracy within ±0.20 mm for all specimens
- Smooth toolpath execution and consistent material removal

In general, the testing demonstrates that the developed CNC system provides good precision and repeatability in the processing of multi-materials, which are relevant in educational laboratories, prototyping, and in case of small enterprise use. The experimental findings validate the mechanical system design, control electronics and software management, showcasing a synchronized system capable of converting CAD/CAM designs into dimensionally accurate parts.

**Table 3.** Positional accuracy and repeatability for X, Y, Z axes

| Axis | Travel Distance (mm) | Average Deviation (mm) | Repeatability (mm) |
|---|---|---|---|
| X | 100 | 0.08 | ±0.05 |
| Y | 100 | 0.10 | ±0.05 |
| Z | 50 | 0.06 | ±0.05 |

**Table 4.** Milling performance for different materials

| Material | Feed Rate (mm/min) | Spindle Speed (rpm) | Surface Roughness Ra (µm) | Dimensional Accuracy | Observations |
|---|---|---|---|---|---|
| Pine Wood | 800–1000 | 10,000–12,000 | 2.3–2.7 | ±0.15 mm | Smooth, stable, no vibration |
| Acrylic | 500–700 | 9,000–11,000 | 2.8–3.2 | ±0.18 mm | Uniform surface, minor chip adhesion |
| Aluminum 6061 | 200–350 | 7,000–9,000 | 5.0–6.0 | ±0.20 mm | Slight vibration at higher feed, acceptable cut |

**Results and Discussion**

Systematic evaluation of positional accuracy and repeatability of the fabricated 3-axis CNC milling machine was done across all three axes. Table 3 summarized the results of which revealed that the X-axis had a mean deviation of 0.08 mm, the Y-axis 0.10 mm and the Z-axis 0.06 mm, and repeatability of ±0.05 mm in each axis. These findings imply that the machine can be trusted to conduct small-scale manufacturing and teaching prototyping operations. Small discrepancies observed are consistent with similar low-cost CNC systems and is due to minor lead screw backlash and frame compliance. In general, the measurements show that the machine offers reliable positioning to execute toolpath with precision.

Pinewood, acrylic and aluminum 6061 sheets were used as representative materials to measure the milling performance. The mean values of surface roughness were about 2.5 µm in pinewood, 3.0 µm in acrylic and 5.5 µm in aluminum, with the maximum feed rate of 1000 mm/min, 600 mm/min, and 300 mm/min respectively, which indicated the ability of the machine to operate with different hardness of the material. Pinewood and acrylic samples showed a mirror-like texture with a small number of tool impressions while the aluminum needed lower feed rates because small vibrations appeared due to compliance with the frame. Testing did not find any stepper motor skips or G-code execution errors. These findings prove that the CNC system is capable of handling soft and light metal materials within its design specifications whilst producing reasonable surface quality and dimensional accuracy as also indicated in Table 4.

The software and control system were tested by running of pre-programmed G-code toolpaths. The machine performed steady and coordinated multi-axis motion, and homing routines demonstrated reliability, maintaining consistent starting positions throughout successive operations. The open-source GRBL firmware was found to offer enough control to develop the 3-axis operations without proprietary modules being needed, and so the usefulness of open-source and low-cost electronics to develop precise motion control became confirmed.

The overall cost of the materials and electronics was around 450 dollars, which is 80-90% cheaper than similar commercial CNC systems, which would cost between 2500 and 5000 dollars. The design of the modular hardware can be upgraded later without any significant redesign, like more powerful motors or spindle improvements, to provide the flexibility to modify the hardware design to suit the changing needs of the application.

In general, the designed CNC milling machine finds a balance between functionality and price. The system is not very flexible in cutting heavy metals due to structural rigidity although it is very compatible with soft metals, plastics, and wood machining and educational/prototyping. Combination of open-source electronic and programming technologies shows that it is possible to use a high-quality CNC machine in a small laboratory or DIY setup. Machining accuracy can also be increased with minor design modifications such as reinforcement of frames and use of anti-backlash lead screws.

Compared to the literature, it shows that the accuracy and repeatability of the machine is similar to other reported low-cost CNC systems, and reducing the cost significantly makes the machine more accessible to small enterprises and academic laboratories. The suggested design facilitates practical prototyping and learning and is able to bridge the gap between theoretical learning and real-life manufacturing experience.

## Conclusion and Future Work

An affordable 3-axis CNC milling machine was efficiently designed, constructed, and evaluated by means of open-source electronics and software. The system proved to be positionally accurate and repeatable to within ±0.05–0.10, which substantiated the hypothesis that the system is applicable in small-scale manufacturing, prototyping, and education. Milling operations conducted on wood, acrylic, and soft aluminum validated consistent multi-material machining adhering to the design constraints. GRBL-based control combined with the use of modular hardware enabled easy operation, design, and low-cost assembly resulting in a total cost of the system of about $450, a saving of 80-90 percent of the price of commercial CNC machines. In general, the suggested design will offer an affordable alternative to expensive industrial systems, facilitating hands-on learning, prototyping, and operations of small enterprises.

Future development will involve improving the structural rigidity of the frame to minimize vibration and performance with harder material, and the use of anti-backlash lead screws to further increase axis accuracy. More profile machining can be performed by upgrading the spindle motor to higher speed and torque. It is also intended to integrate real-time feedback sensors in order to be able to correct errors automatically and to have increased repeatability. Moreover, increasing software compatibility with more advanced CAM tools will permit more complex machining operations, and a 4th axis or rotary attachments may make multi-axis machining possible with advanced applications. These enhancements will make the machine more versatile and precise, allowing it to be used in industrial, educational and research settings without increasing costs.

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