Low-Cost, Flexible Multi-Fabrication CNC: A Modular Approach for Drilling, Laser Engraving, and Multi-Color Pen Plotting

Kris Sucharitakul, Weon Keun Song, Prachaya Praphaphan, Tanapatra Boonsar, Supun Dissanayaka

***Abstract*— CNC, also known as Computer Numerical Control machines, are commonly used in both large and small-scale manufacturing businesses due to the automated machine capabilities enabling productive and efficient manufacturing processes with minimal human intervention. However, small manufacturing businesses and startups often face cost and space management challenges when utilizing multiple CNC machines for various tasks such as CNC Milling, Turning, Drilling, and Laser-Engraving etc. Inspired by the simple design of a pen plotting machine, this paper explores the potential for a modular, multi-functional CNC machine that integrates Multi-Color Pen Plotting, Drilling, and Laser-Engraving processes into a single system. By enabling tool interchangeability and frame scalability, our system eliminates the need for separate devices. Unlike similarly priced multi-fabrication machines, which typically lack a milling or drilling option and are limited by the cutting depth of the laser module, our machine includes a drilling module that allows for deeper material penetration, handling metal, wood, or acrylic sheets thicker than 70 mm and a laser module effective for engraving and achieving a cutting depth of 7mm with 1 pass. Our Pen plotter design minimizes wear on the XY gantry by eliminating the need for recalibration between color pen changes due to the unique design of the five-color pen holder. Additionally, if there is no movement in the tool change, only calibration for the Z-axis is required. Therefore, our design is an ideal solution for small businesses seeking efficient and scalable fabrication capabilities.**

***Keywords*— CNC, Laser Engraving, XY Plotter, Pen Plotting, Tool Changing, CNC Drilling.**

I. INTRODUCTION

Pen plotters were introduced in 1959 by American companies Benson and CalComp [1] to automate technical and engineering drawings. CalComp’s early 12-inch sprocket-feed plotter, driven by stepper motors, struggled with diagonal lines due to limited motor control [2]. In contrast, European firms like Aristo and Zuse KG (Germany), Kongsberg (Norway), and Contraves AG (Switzerland) developed more precise, numerically controlled machines [3].

Widely adopted in architecture, engineering, and cartography, pen plotters saw rapid advancements in the 1970s and 1980s. Innovations such as Hewlett-Packard’s micro-grip design led to faster, more affordable devices with features like automatic pen changers, sheet feeders, and acceleration up to 6g. By the 1990s, electrostatic, inkjet, and laser printers largely replaced them. However, companies like Roland and Mutoh continued to produce vinyl cutting plotters—mechanically similar to pen plotters—which gained popularity in the arts and crafts sector. Today, pen plotters serve niche markets like generative art and labeling [3].

Plotters came in various configurations based on space, surface type, and drawing tools. Common types included drum, micro-grip, and flatbed plotters. Drum plotters (Fig. 1) used a rotating drum for X-axis motion and a pen moving along the Y-axis. They were compact and suitable for large-format drawings, making them popular in design offices. Flatbed plotters (Fig. 2), with a stationary surface and X-axis gantry for Y-axis movement, had a footprint equal to the drawing area—an approach adopted in our own mechanical design.

Fig. 1 CalComp 565 [1]

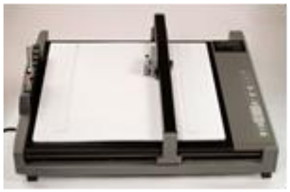

Fig. 2 Flatbed plotter [3]

Although largely obsolete, XY plotters have recently gained popularity among generative artists, designers, and tech enthusiasts. An active online community now shares ideas, techniques, and upgrades for pen plotters [4]. Our design goes beyond hobby use, aiming to enhance functionality with multi-color drawing, laser engraving, and drilling—broadening its industrial and educational applications.

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II. LITERATURE REVIEW

CNC plotters, also known as XY plotters, merge traditional plotting with modern computer control to produce accurate drawings and geometric designs [5]. They use stepper motors and ball screws for precise tool head movement along the X and Y axes. While CNC plotters are used for plotting, other CNC machines can also handle tasks like laser engraving, drilling, cutting, and 3D printing.

XY plotters offer key advantages over traditional printing, particularly in technical fields like engineering, circuit design, and architecture, where fine detail is essential [6]. They also handle large-format drawings more affordably than standard printers.

Despite these strengths, most XY plotters remain inflexible and single purpose. This paper introduces a low-cost, modular multi-fabrication CNC plotter that supports multicolor drawing, laser engraving and cutting, and drilling. We developed a new jig fixture for tool swapping and custom software to overcome limitations found in existing open-source systems.

III. STRUCTURAL FRAMEWORK DESIGN

A. Gantry and Motion System

Our machine is based on a Cartesian gantry configuration designed for modular tool head integration: The X-axis and Z-axis are driven by a single NEMA 23 motor. The Y-Axis, which carries the heaviest load, is driven by two NEMA 23 motors to maintain gantry straightness and minimize deflection.

The frame is constructed primarily from aluminum profiles of the 20-series and 30-series for optimal strength-to-weight ratio. All moving components and load-bearing structures are made of metal to ensure precision and reduce deformation risks. 3D-printed Plastic components are exclusively for non-load-bearing parts and not directly connected to other plastic parts, ensuring either metal-to-metal or metal-to-plastic interfaces for better structural integrity.

The entire frame is designed to be scalable, supporting work surfaces up to 1m x 1m with the current NEMA23 motors. Scaling requires only the purchase of appropriately sized aluminum profiles, linear rails, and ball screws, enabling straightforward customization for larger work areas. This can be seen in Appendix 1 and Appendix 2.

Machining tolerances are controlled as follows: Metal-to-metal interfaces were machined to ±0.01 mm. 3D printed plastic parts are fabricated with a tolerance of ±0.15 mm.

Additionally, the Y-axis gantry plate is designed to accommodate a drilling spindle offset of approximately 60 mm (refers to Fig. 3). Combined with the Z-axis offset, the total lateral displacement from the Y-axis rail centerline is approximately 135 mm. This offset is accounted for during the frame's Finite Element Method analysis to ensure stability under dynamic loads.

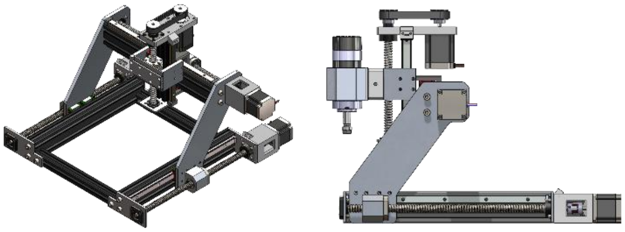

Fig. 3 Isometric view of the frame and
Side view showing Y-axis Gantry offset

B. Motion System Components

NEMA 23 stepper motors with torque ratings of 1.26 Nm and 1.89 Nm selected based on motion simulations conducted using SolidWorks. A maximum motor torque of 0.9 Nm is identified in simulation analysis in SolidWorks, providing a safe operational margin. Each motor is paired with appropriate motion transmission systems: Ball screws for the X and Y axes to enable high-torque travel. Belt drive for the Z-axis to save on vertical space. Micro stepping at 1/16 subdivision is used to achieve motion resolutions of: 0.0125 mm/step for X and Y axes 0.005 mm/step for Z-axis. These resolutions are sufficient to support both plotting and drilling operations.

C. Modular Tool head Interface

Modular tool head mounting mechanism uses a precision-machined dovetail sliding joint that refers to Fig. 4: Z-axis end effector mount (DSG16H) fabricated from aluminum and features a 1 mm chamfer to prevent scraping of the 3D-printed plastic dovetails on individual tool heads. Standardized dovetail interface measures 98 mm in length and 7 mm in depth to provide a high contact surface area and ensure mechanical rigidity. Base length of the mounting system is determined by the largest tool head the drilling module. Dovetail joint allows for rapid tool head changes while maintaining alignment accuracy, essential for modular operation across different machining tasks.

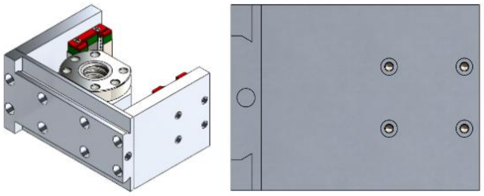

Fig. 4 Isometric and side view of the Z-Axis Dovetail joint

D. Modular Tool head Interface

The modular tool heads feature 3D-printed dovetails designed as sacrificial components, protecting the aluminum Z-axis dovetail from wear during frequent tool changes. The use of 3D printing for these parts ensures low-cost, easy fabrication and allows for quick replacement once wear impacts alignment accuracy, maintaining the overall system's precision.

Drilling/Spindle Module

The aluminum spindle clamp, measuring 62 × 102 mm, serves as the reference for all dovetail-connected modules. Cutting parameters, such as feed rate and plunge speed, are calibrated to minimize vibration based on spindle torque and material properties. Testing confirmed minimal spindle runout and frame oscillations at 200 mm/min.

Fig. 5 Tool head mount attached to the spindle clamp

Laser Engraving Module

The laser module features a fixed 40 mm focal length. The tool head, shown in Fig. 6, includes a 40 mm offset from the work surface, adjustable via the Z-axis ball screw to accommodate differing material thicknesses. Power control and focal calibrations optimized engraving sharpness and depth across acrylic, wood, and anodized aluminum.

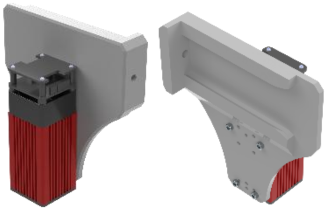

Fig. 6 Tool head mount attached to the laser module

Pen Plotter Module

The Plotter module, shown in Fig. 7, uses a rotary pen changing mechanism, eliminating the need for homing or moving to designated pen swap spots like conventional designs. This increases active plotting time and shortens the duration for multi-color plotting.

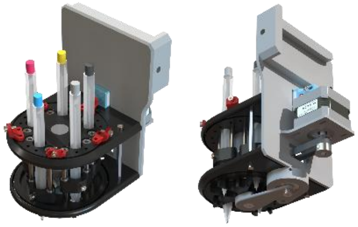

Fig. 7 Tool head mount attached to the pen plotter module

E. Modular Work Surface Design

The system incorporates three interchangeable modular work surfaces, slotted directly into the CNC frame: The T-slot with an MDF base (380 × 400 mm) designed for the drilling module, enabling easy clamping of workpieces with pre-drilled pilot holes for versatile fixtures refers to Fig.8. The 3mm Acrylic Topper used with the pen plotter module, providing a smooth, low-friction surface refers to Fig.9. The laser dissipation tray designed to absorb excess laser energy, made from folded metal refers to Fig.10. The work surfaces are easily swapped without disassembling the main gantry, supporting rapid transitions between machining modes.

F. Embedded Electronics and Control

Main Control Unit

The Multi-Fabrication CNC depends on the MKS-DLC32 motherboard for stable, error-free operation [7]. Powered by a dual-core 240 MHz ESP32, it supports Wi-Fi, Bluetooth, and multiple interfaces (UART, SPI, I2C) for wireless control and sensor feedback. The board handles up to 4-axis motion, spindle/laser PWM, and probe sensing, with a MicroSD slot for offline G-code and a USB-C port for firmware updates.

However, this unit provides limited power which is insufficient to ensure the movement of all attached motors. Therefore, it is necessary to implement four stepper motors DM542s for the move for the movements of two x-, one y- and one z-axis, respectively.

Step driver contains a DM542s monolithic power IC designed for driving two-phase bipolar stepper motors with input voltages ranging from 9V to 42V DC and adjustable output current from 0.5A to 4.0A via DIP switches. It supports micro stepping resolutions from full-step to 1/19-step for smoother and quieter motion control.

The current tuning for DM542s Subdivision setting is 1 Micro step 200 Pulse/rev and Current setting is 2A - 2.2A peak current.

The entire system is powered by two industrial grade switching power supplies. One power supply, rated at 24V 15A, powers the electronics, logic systems, and stepper drivers. The other, rated at 48V 15A, is dedicated to high-power components such as spindle motors or laser modules. This configuration ensures reliable energy delivery across all subsystems.

Each power supply unit contains an internal high-frequency transformer, rectifier circuit, and voltage regulation module to ensure efficient conversion from AC mains (110–220V) to stable DC output. These units feature surge protection and built-in cooling via aluminum heat sinks and internal fans, maintaining thermal stability for continuous operation.

Fig.8 T-slot MDF Base

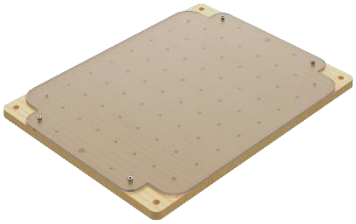

Fig. 9 Acrylic topper on top of MDF Base

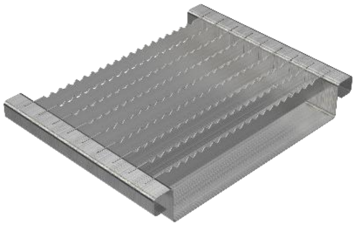

Fig. 10 Laser dissipation tray

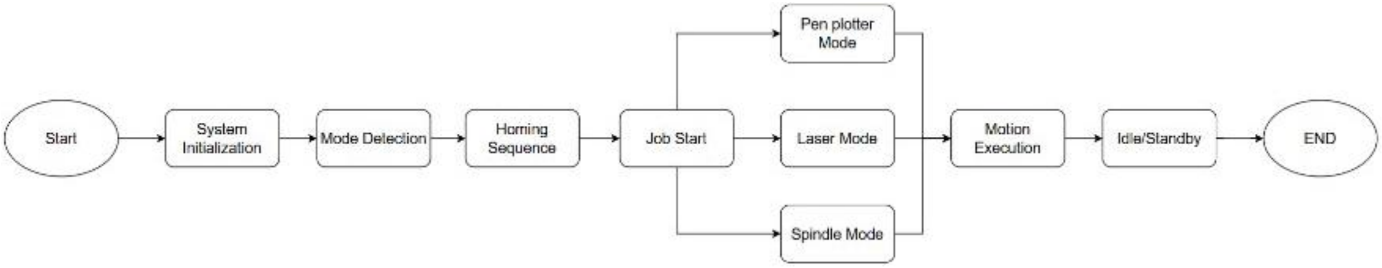

Fig. 11 Control Sequence

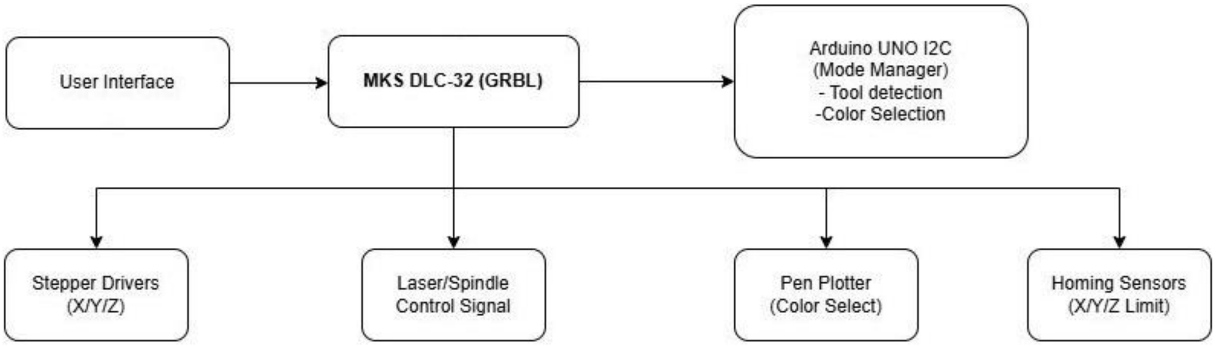

Fig. 12 Overall control system

IV. DESIGN CALCULATIONS

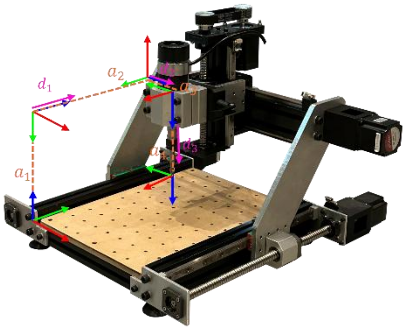

Fig. 13 Structural design with assigned axes

Forward kinematics determines the position and orientation of the tool head of a 3-axis CNC machine in the workspace based on the joint angles or positions of the axes of the machine. In a typical 3-axis machine, the axes are usually linear and orthogonal, corresponding to the X, Y, and Z directions [8]. Forward kinematics is expressed by the transformation matrix refers to (1).

$$T = \begin{bmatrix} 0 & -1 & 0 & a_3 + d_2 \\ -1 & 0 & 0 & a_2 + d_1 \\ 0 & 0 & -1 & a_1 - a_4 - d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The inverse kinematics for the X, Y and Z axis of our 3 axis machine is described by (2) as follows for the X axis where the N is the number of steps on the axis, x is the position with respect to workspace, d is the lead distance of the axis screw and the α is the axis motor step angle. Same principle applies to the Y axis

$$N = \frac{2\pi x}{d\alpha} \tag{2}$$

Assuming friction is negligible, the relationship between the force F (N) exerted on the mass m (Kg) of the tool head and the torque T (Nm) generated by the motor on the screw is given by equation (3) refers to Fig. 14.

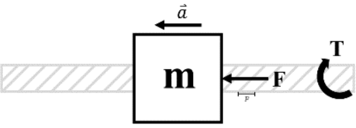

Fig. 14 Force Diagram

Where η is lead screw efficiency and p is the pitch of lead screw.

$$T = \frac{F.p}{2\pi.\eta} \tag{3}$$

The relation between angular distance θ (rad) of the lead screw and translation d (m) of tool head mass m (Kg) describe by (4) as follows.

$$d = \frac{p.\theta}{2\pi} \tag{4}$$

Velocity (5) and the acceleration (6) of the tool head are then derived using (3).

$$\dot{d} = \frac{p.\dot{\theta}}{2\pi} \tag{5}$$

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$$\ddot{d} = \frac{p.\ddot{\theta}}{2\pi} \tag{6}$$

Since we utilized trapezoidal velocity profile, maximum acceleration and jerk can be expressed by (7) and (8) respectively.

$$\ddot{d}_{max} = \frac{\dot{d}_{max}}{t_{blend}} \tag{7}$$

$$J = \frac{\ddot{d}_{max}}{t_{blend}} \tag{8}$$

Let s and s' denote the current and target steps per millimeter setting for each motor, while l and l' represent the current and intended output distance, respectively. This same principle can be applied for all axes.

$$s' = \frac{sl'}{l} \tag{9}$$

V. CONTROL SOFTWARE

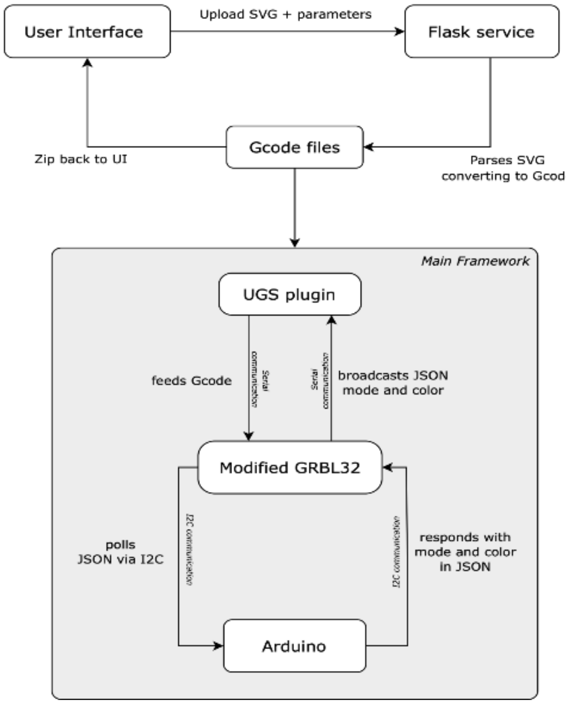


Fig. 15 Software framework

Once a user uploads SVG (scalable vector graphic) into the web UI, the Flask service converts image into colors-layered G-code, which the UGS (universal G code sender) plug-in streams over serial to a modified GRBL32 firmware. GRBL32 polls the Arduino every second via I²C to request a JSON snapshot containing the active tool mode and CMYK color. It then rebroadcasts this JSON data. The I²C communication is bidirectional: GRBL32 initiates polling to retrieve machine mode, and the Arduino (MKS) responds with the JSON for color selection.

GRBL32 also sends a concise [MODE:x] tag back to UGS every 1 second. When a $CC, $CM, $CY, or $CK token is received by the modified GRBL32, it forwards the command to the Arduino. The Arduino then confirms that the pen plotter has rotated, and GRBL32 resumes the job which maintains tight, automated synchronization between the UI, firmware, and color-selection hardware.

VI. RESULTS

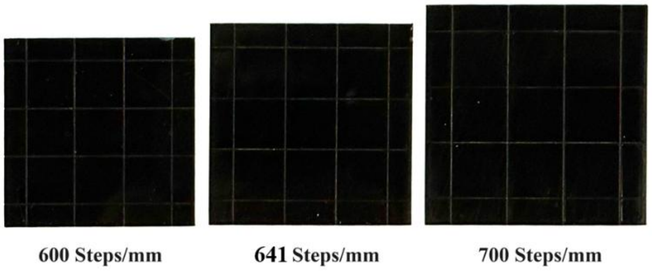
A. Determination of Optimal Step Resolution

Table I presents the results of test laser cuts performed using various step resolutions on the X-axis motor. Each trial aimed to achieve a target cut length of 100 mm (Fig. 16).

TABLE I
LASER CUTTING LENGTH

Resolution (step/mm)	Output length (mm)	Desired length (mm)
650	101.46	100
625	97.56	
600	93.66	

To obtain precise cut lengths, step resolution of the motor is calibrated in accordance with Equation (9). By utilizing one of the test parameters, the precise step resolution necessary to achieve accurate cut lengths determined as 641 steps/mm.



600 Steps/mm **641** Steps/mm 700 Steps/mm

Fig. 16 Precision Step Calibration Grid with Laser Cutting

B. Positional accuracy/Backlash

The pen plotter is chosen to test positional accuracy due to the precision and minimal material waste. The laser module, while capable of marking lines as thin as 0.5 mm, tends to burn and widen with multiple passes. The milling module is slower, messier, and consumes more costly material. Using 0.5 mm ballpoint pens, we first plotted a control grid (3×3 squares with 10 mm spacing) 30 times without removing the tool head to observe any natural line thickening from repeated passes. Then, for the test, we repeated the same 30-pass grid without re-homing the axes, removing and remounting the pen plotter head with moderate force after every pass. Any deviation or thickening beyond the control grid indicated backlash introduced by mechanical misalignment during remounting. However, there is no significant visual difference between the line thicknesses of the control and the test grid. Meaning little to no backlash refers to Fig. 17.

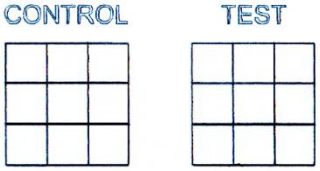


Fig. 17 Backlash test

C. Pen plotter Mechanism

Mechanism Misalignment test

Resolution tests confirmed a minimum effective stroke accuracy better than 0.15 mm across the full plotting area when no color change is used. Drawing capabilities can be seen in Appendix 3.

The multi-color pen plotter uses a rotary cam to select pens, with the deepest part aligning the active pen. Due to budget constraints, some components were 3D printed, resulting in minor misalignments between pen positions. To evaluate this, the square grid from Fig. 17 was plotted 30 times with a color change after each pass. X and Y offsets were measured after each pass. The results showed small variations, with a maximum observed offset of 0.58 mm—within acceptable tolerance for the application (Fig.18).

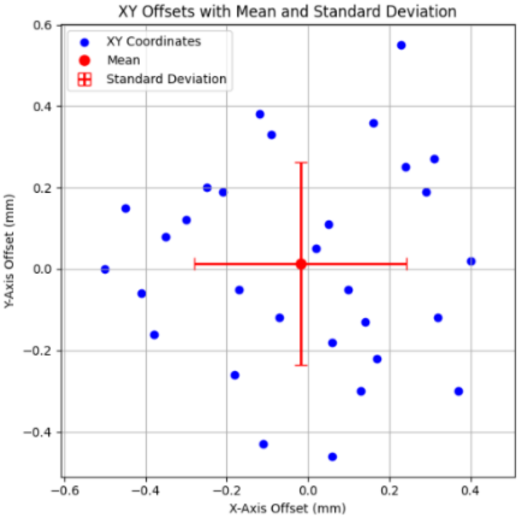


Fig. 18 Pen plotter misalignment test

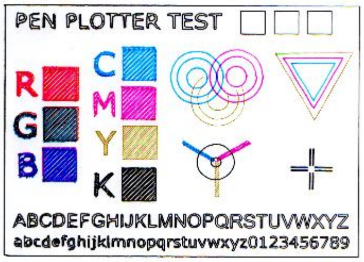


Fig. 19 Multi-color pen plotter calibration

D. Laser Module

The 40W laser module demonstrated the ability to accurately engrave wood and acrylic at a power level of 15W and as low as 10% of that setting (Fig.20). It successfully cut the calibration block's borders at full power (40W) in a single pass.

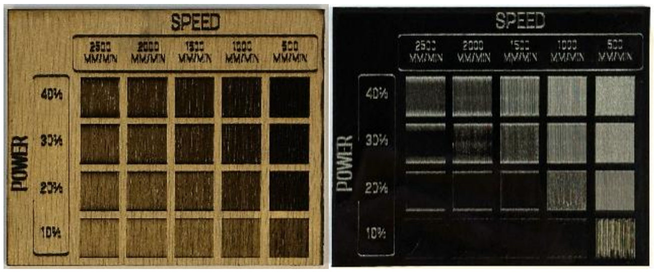


Fig. 20 Laser Engraving Calibration (15W)

Furthermore, the module achieved clean cuts through 7mm plywood and dark acrylic in one pass, with thicker materials requiring multiple passes (Fig.21).

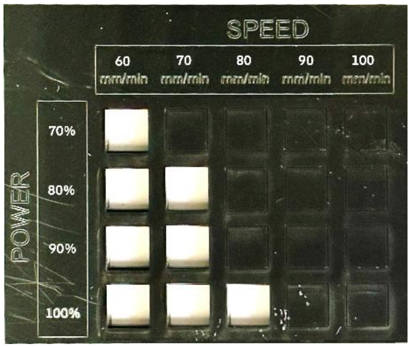


Fig. 21 Laser Cutting Calibration (40W)

E. Milling Module

To evaluate the cutting precision of the machine, tests were performed on 10 mm thick 6061 aluminum using cuts of increasing depth. In Fig. 22, the machine made a sequence of straight cuts as follows:

- A 20 mm long cut at a depth of 2 mm.
- A second 20 mm long cut at a depth of 4 mm, positioned with a 0.5 mm lateral offset from the first cut.
- A third 20 mm long cut at a depth of 6 mm, with a 1.0 mm lateral offset from the first cut.

This sequence shows how the cut position shifts as the depth increases. In Fig. 23, the same test was repeated with tighter tolerances. Each successive cut was offset by only 0.1 mm, providing a more precise assessment of the machine's accuracy at small deviations. An example of how the cut was made can be seen in Appendix 4 and Appendix 5

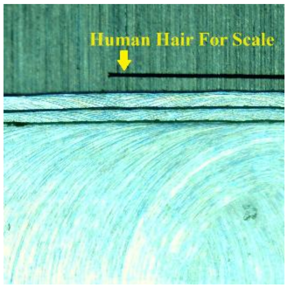


Fig. 22 0.5mm spaced steps

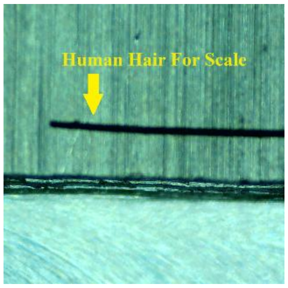


Fig. 23 0.1mm spaced steps

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CONCLUSION

The results demonstrate that our modular, scalable CNC machine achieves high precision across multiple fabrication modes. Optimal step resolution calibration (641 steps/mm) ensures machine accuracy (Fig. 16), while backlash testing confirms reliable positional accuracy (Fig. 17). The multi-color pen plotter shows minimal misalignment within acceptable tolerances (Figs. 18–19), and the laser and milling modules perform both engraving and cutting accurately on wood, acrylic, and aluminum (Figs. 20–23). These findings validate the system's effectiveness for multi-functional, low-cost fabrication.

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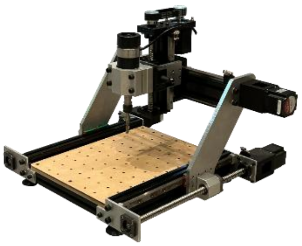
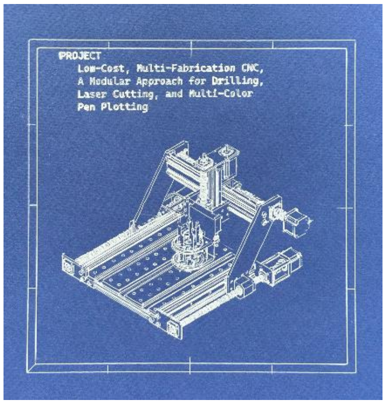
APPENDIX

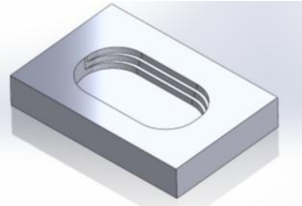


Appendix 1.
Image of the actual machine and work surface

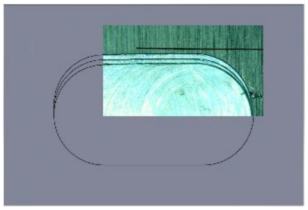
Appendix 2.
Rendering of the 1m x 1m work surface machine



Appendix 3.
Drawing created by the pen plotter



Appendix 4.
Isometric view of how the aluminum cuts were made



Appendix 5.
Top view of how the aluminum cuts were made

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