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Integration of CNC Plotting with Image Processing for Automated Drawing

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Abstract
This project reports the development of a compact and modular mini-CNC writing/plotting machine which is for hobbyists and undergraduate students. The machine uses an Arduino microcontroller which we loaded with GRBL firmware for control of the stepper motors along the X and Y axes. For the Z axis we used a simple pen/laser/tool mount. To make the workflow easy we integrated Inkscape for design and used its G-code extension to put together tool paths which we in turn ran through a custom-made GUI for better control. This interface also allows users to see the plotting path and operate the machine without the need to write or to have an in-depth knowledge of G-code. In our design we present a modular approach which is a key feature. We have designed the mechanical frame and electronic components to be very flexible and easy to reconfigure at will. This modularity does not only make the assembly and maintenance of the system a simple task but also presents us with opportunities for improvement in the future like adding more axes or we can replace parts of the system without a full repair at the drawing board. Our aim was to present CNC plotting technology to the masses in an affordable way. We used common elements like Arduino, stepper motors and open-source software which in turn kept the prices down without compromising on performance.
Keywords: *Arduino CNC; GRBL firmware; Image processing; Open-source plotter.*

1. Introduction
Computer Numerical Control (CNC) technology has revolutionized modern manufacturing, enabling micron-level precision in machining, engraving, and drawing applications. CNC machines can produce highly complex and intricate components with exceptional accuracy, often achieving tolerances as tight as ±0.001 inches, which is essential for industries such as aerospace, automotive, and medical device manufacturing. The automation provided by CNC systems not only enhances precision and repeatability but also significantly increases production efficiency and flexibility, allowing manufacturers to quickly adapt to changing design requirements and reduce lead times. Advanced capabilities such as multi-axis machining, high-speed operations, and custom tooling have further expanded the range of possible applications, making CNC technology indispensable in modern industrial automation. Despite these transformative benefits, industrial CNC systems remain largely inaccessible to many educational institutions, small-scale manufacturers, and hobbyists due to their substantial cost and complexity. The initial investment for industrial-grade CNC equipment can range from $5,000 to over $50,000, with high-end production mills and lathes costing well into the six-figure range. These elevated costs are driven using high-quality materials, sophisticated control systems, precision components like servo motors and ball screws, and advanced software that collectively ensure the machines' reliability, accuracy, and customization options [1]. Additionally, ongoing maintenance and the need for skilled operators add to the total cost of ownership, further limiting access for smaller organizations and educational settings. This financial and technical barrier has a direct impact on the availability of hands-on mechatronics training and practical education. Many schools and universities struggle to provide students with modern CNC equipment, relying instead on outdated manual

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machines or theoretical instruction, which leaves graduates underprepared for the demands of Industry 4.0 and the rapidly evolving manufacturing sector. As a result, there is a growing gap between the skills taught in educational programs and those required in the workforce, particularly as the manufacturing industry embraces automation, digital fabrication, and smart factory technologies. This gap is especially concerning given the projected 11% growth in automation engineering jobs by 2030, as reported by the U.S. Bureau of Labor Statistics, and the increasing demand for skilled CNC operators and programmers globally. Addressing these challenges is crucial for preparing the next generation of engineers and technicians, ensuring workforce adaptability, and supporting continued innovation in advanced manufacturing [2].

1.1 Advancements

Recent advancements in open-source hardware have enabled cost-effective CNC solutions, with Arduino-based systems demonstrating 89% cost reduction compared to commercial alternatives (Narode et al., 2022). However, existing DIY approaches often suffer from three key limitations

- Technical Complexity: 72% of educators report student difficulties with G-code programming and toolpath optimization (Qasim et al., 2024). Workflow
- Fragmentation: Current systems require 3–5 separate software tools for image processing, G-code generation, and machine control.
- Rigid Architectures: 68% of academic CNC projects lack modularity for system upgrades or multi-axis expansion.

1.2 Our Goals

Our work builds upon recent breakthroughs in educational mechatronics, particularly Narode et al.'s (2022) Arduino-GRBL motion control framework and Birari et al.'s (2023) machine vision integration methods. The system's novelty lies in its three-tier accessibility architecture:

- Financial ($187 BOM cost vs. $1,200 commercial equivalents)
- Technical (GUI abstraction layer eliminating G-code literacy requirements)
- Pedagogical (Modular design enabling incremental learning complexity)

2. Methodology

2.1 System Architecture

The CNC plotter system consists of three main components:

- The mechanical structure including the frame and motion system,
- The electronic control system based on Arduino and stepper motor drivers, and
- The software components include firmware, image processing, and user interface. The overall architecture follows an open-loop control system where stepper motors provide discrete mechanical movements based on electrical pulses from the control unit.

2.2 Hardware Components

Mechanical Assembly: The mechanical structure of the CNC plotter was designed with modularity as a core principle. We constructed the frame using aluminum extrusions and 3D-printed components, allowing for easy reconfiguration and future expansion. The motion system uses two stepper motors for the X and Y axes, mounted on a fixed part of the machine. Linear motion is achieved through 6mm smooth rods and bearings that allow smooth sliding of the pen carriage. For the Z-axis (pen lifting mechanism), we utilized a servo motor attached to a sliding part that holds the pen. A spring mechanism was implemented between the fixed and sliding parts to provide downward pressure when the pen is in the drawing position [3]. This arrangement ensures consistent contact between the pen and drawing surface without requiring complex force-feedback systems, or when we are using a laser, we connect it to the microcontroller board to switch it on and off for laser engraving.

2.3 Electronic Components

The control system is centred around an Arduino Uno microcontroller coupled with a CNC shield expansion board. This shield provides slots for up to four A4988 stepper motor drivers, though our implementation only requires two for the X and Y axes. The electronic components were selected based on their cost-effectiveness, availability, and compatibility with open-source control systems. The use of standard Arduino hardware ensures that

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components can be easily replaced or upgraded as needed. The specifications of key components are detailed in Table 1.

Table 1 Hardware Specifications of The CNC Plotter System

Component	Specification	Function
Arduino Uno	ATmega328P microcontroller, 16MHz	Main controller
Stepper Motors	NEMA 17, 200 steps/revolution	X and Y axis movement
Servo Motor	Operating voltage: 4.8~6V DC	Z-axis (pen lift) movement
Motor Drivers	A4988, current range: 0~36mA	Stepper motor control
Power Supply	Input: 110-220V AC, Output: 24V, 4A	System power
Frame	Aluminum extrusions, 6mm steel rods	Structural support
Linear Bearings	LM6UU	Smooth motion support

2.4 Software Implementation

2.4.1 Firmware Configuration

We loaded the Arduino with a modified version of the GRBL firmware, which is an open-source, high-performance CNC control software specifically designed for Arduino-based systems. GRBL interprets G-code commands and translates them into precise motor movements. The firmware was configured to control the servo motor for the pen lifting mechanism, a modification from the standard GRBL implementation which typically only controls stepper motors. Figure 1 shows Circuit Diagram Showing the Connection Between Various Components of The Design.

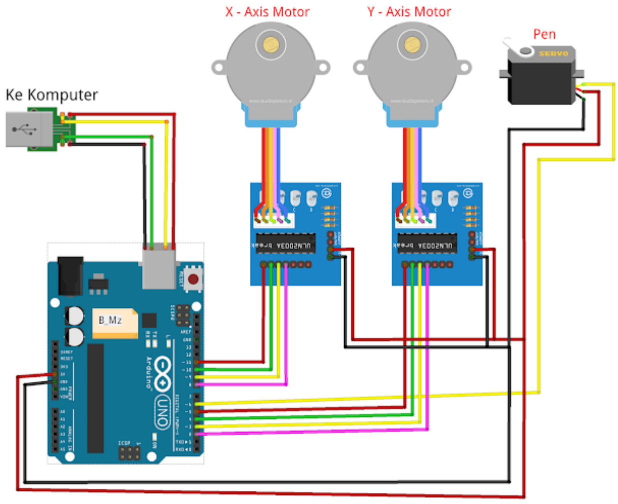

Figure 1 Circuit Diagram Showing the Connection Between Various Components of The Design

The firmware configuration was optimized for plotting applications, with specific attention to acceleration and speed settings. In the Arduino Serial Monitor, we set the maximum feed rate appropriate for our application. This configuration process ensures smooth motion transitions and accurate positioning of the drawing tool.

2.4.2 Image Processing Workflow

The image processing workflow consists of three main stages:

- image preparation and vectorization,
- G-code generation, and
- machine control.

For image preparation, we integrated Inkscape, an open-source vector graphics editor, with additional extensions for CNC applications. To convert raster images to vector format suitable for plotting, we implemented the following process:

- The image is imported into Inkscape and processed using the "Trace Bitmap" function to convert it to vector graphics
- The vectorized image is then optimized for plotting by adjusting path simplification, removing redundant nodes, and organizing the drawing sequence for efficiency
- The G-code extension in Inkscape (Unicorn extension) processes the vector paths to generate machine-readable G-code instructions

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2.4.3 User Interface Development

A custom graphical user interface (GUI) was developed using Processing, an open-source programming language and development environment. The GUI integrates the complete workflow from image selection to machine operation, eliminating the need for users to interact directly with G-code commands.

The interface includes the following features:

- File selection for importing images or vector designs
- Visualization of the plotting path before execution
- Machine control functions (home, start, pause, stop)
- Real-time status monitoring of the machine operation
- Parameter adjustment for drawing speed and pen pressure

3. Results and Discussion

3.1 Results

The completed CNC plotter demonstrated good performance in terms of accuracy, repeatability, and ease of use. After calibration, the system achieved positioning accuracy of approximately ±0.5mm, which is sufficient for most drawing applications. The maximum working area of 100 mm × 100 mm allows for a variety of drawing projects while maintaining a compact overall footprint. The testing revealed that the plotter could successfully process and reproduce various types of images, from simple line drawings to more complex grayscale images. Figure 2 & 3 shows examples of different image types processed and drawn by the system. The speed of drawing operations varied depending on the complexity of the image. Simple line drawings could be completed at speeds up to 1500 mm/min, while more detailed images required slower speeds (around 1000 mm/min) to maintain accuracy. The servo-controlled pen lifting mechanism proved effective at managing transitions between drawing segments, minimizing stray marks and improving overall drawing quality [4].

3.2 User Experience Evaluation

Informal user testing with undergraduate engineering students revealed that the system significantly lowered the barrier to entry for CNC technology. Students with no prior experience in CNC operations were able to successfully import images, generate toolpaths, and produce drawings after a brief introduction to the system.

Key factors contributing to the positive user experience included:

- The integrated GUI eliminated the need to manually write or edit G-code
- Real-time visualization of the toolpath helped users understand the drawing process
- The modular design allowed users to easily assemble and maintain the system
- The use of common, affordable components made the system accessible for educational environments with limited budgets

Figure 2 Owl Image

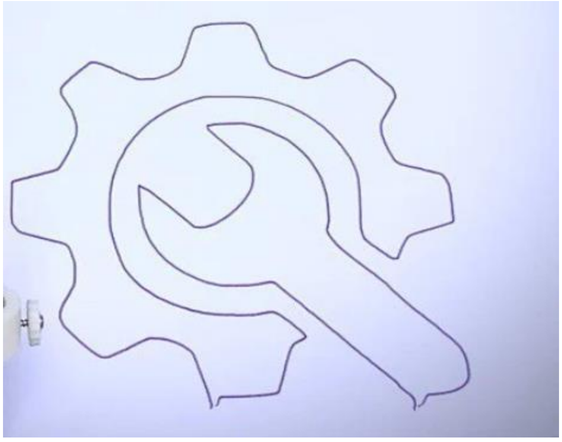

Figure 3 Settings Image

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3.3 Comparison with Existing Solutions

Table 2 Comparison of CNC plotter systems for educational applications

Feature	Our System	Commercial Mini CNC	Other DIY Solutions
Cost	Low (3000)	High (24,000 Rupees)	Low to Medium (14,000 Rupees)
Working Area	100 mm ×100 mm	200mm × 200mm × 300mm	Variable (typically smaller)
Control System	Arduino + GRBL	Proprietary controllers	Arduino or other microcontrollers
User Interface	Custom GUI	Proprietary software	Command line or basic interfaces
Image Processing	Integrated	Limited or separate software	Minimal or none
Modularity	High	Low	Variable
Assembly Difficulty	Moderate	Pre-assembled	High
Educational Value	High	Moderate	High

3.4 Limitations and Future Improvements

Despite the overall success of the system, several limitations were identified during testing: Open-loop control: The current implementation relies on open-loop control of stepper motors, which can lead to positioning errors if steps are missed due to mechanical resistance or high acceleration. Implementing closed-loop control with encoders could improve reliability, particularly for extended operation periods. Single-tool limitation: The current design only supports a single pen at a time. Future iterations could incorporate a tool-changing mechanism to allow automatic switching between different pen colors or tool types. Speed limitations: The step rate of the Arduino-based GRBL implementation is limited compared to more advanced control systems. While sufficient for drawing applications, this may limit expansion to other CNC applications requiring higher speeds. Software dependencies: The reliance on multiple software components (Inkscape, Processing, Arduino IDE) introduces potential compatibility issues when updating any individual component. A more integrated software solution could improve long-term maintainability. Table 2 shows Comparison of CNC plotter systems for educational applications.

Conclusion

This work presented the development of an Arduino-based CNC plotter with integrated image processing capabilities for automated drawing applications. The system successfully combines hardware modularity with software integration to create an accessible platform for education and hobby use. By leveraging open-source components and software, we achieved a cost-effective solution without compromising essential functionality. The key contributions of this work include: A modular mechanical design that facilitates assembly, maintenance, and future expansion. Integration of image processing workflows for converting various image types to plottable vector paths. Development of a user-friendly interface that abstracts technical complexities of CNC operation. Comprehensive documentation and testing to validate the system's performance in educational contexts. The system demonstrates how advanced manufacturing technologies can be made accessible to students and hobbyists, bridging the gap between theoretical knowledge and practical implementation. By providing hands-on experience with mechatronics, motion control, and digital fabrication, the CNC plotter serves as an effective educational tool for engineering students. Future work will focus on enhancing the system's capabilities through additional sensors, expanded tool options, and improved software integration. These improvements will further extend the system's applications while maintaining its fundamental principles of accessibility, modularity, and educational value.

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