



DESIGN AND EVALUATION OF A WIRELESS MINI CNC PLOTTER USING OPEN-SOURCE HARDWARE

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Abstract

Modern industrial automation relies significantly on Computer Numerical Control (CNC) machinery; however, commercial equipment remains financially restrictive and geometrically bulky for educational laboratories and small-scale electronic production. This research demonstrates the development, systemic layout, and practical evaluation of an affordable, portable, wireless three-axis mini CNC plotter. The system design leverages an open-source ATmega328P microcontroller coordinated with a Cartesian multi-axis motor array to control spatial coordinates (X, Y, and Z planes). An open-source vector graphics processor translates graphical files into hardware-compatible geometric coordinate scripts (G-code). To circumvent the mechanical vulnerabilities and structural constraints of hardwired cables in workstation environments, an IEEE 802.15.4 Zigbee telemetry framework provides continuous, low-latency, wireless data stream distribution to the physical actuation drivers. Empirical testing confirms precise vector path tracking and repeatable micro-stepping positioning accuracy during the execution of intricate graphical paths and dense printed circuit board (PCB) trace patterns. The resulting prototype offers a scalable, low-cost platform for desktop digital fabrication, architectural prototyping, and academic engineering curricula.

Keywords: Computer Numerical Control (CNC), Arduino Prototyping, Micro-stepping Motor Control, Zigbee Wireless Mesh, Digital Fabrication, Vector Graphics, G-code Automation.

1. Introduction

Automated manufacturing tools have undergone major transformations since the inception of industrial mechanization. In early centuries, conventional operations like drilling, milling, and complex lathe contouring depended entirely on manual hand wheel adjustments and persistent human oversight. The modern transition to automated fabrication emerged during the mid-twentieth century when early numerical control principles were established by Parsons [1] to interpolate complex curves utilizing spatial coordinate tables. While these advancements redefined high-volume mass production across industrial segments, standard commercial CNC platforms still present noticeable barriers [2, 3]. These include high capital costs, large structural dimensions, complex maintenance schedules, and the requirement of extensive training for human operators. Consequently, a strong demand has emerged within maker communities, university laboratories, and rapid-prototyping workshops for low-cost, portable, automated drawing and cutting mechanisms.

To address these production challenges, this research presents the engineering and systematic deployment of a mini three-axis wireless CNC plotter using accessible

open-source components and integrated telemetry interfaces. A hardware plotter serves as a highly precise continuous-path drawing instrument that uses coordinate instructions to actuate marker tips over flat substrates [4, 5]. By substituting manual layouts with integrated microprocessors, modern microcontrollers can easily decode multi-axis toolpaths, turning programmatic lines into smooth mechanical movements. The physical machine framework developed in this study guides planar movements over a two-dimensional space through structured three-axis mechanisms (X, Y, and Z vectors) [6]. This highly flexible mechanical arrangement supports specialized low-cost fabrication tasks, such as automated trace routing for printed circuit boards (PCBs), custom emblem branding, and delicate micro-machining operations.

The primary objective of this investigation centres on implementing an open-source microcontroller system combined with affordable stepper and servo motor arrays working over a custom wireless network layer [3, 7]. The physical assembly reads dedicated geometric preparatory instructions, universally classified as G-codes, to manage exact toolpath movements across three dimensions [8]. By routing structured alphanumeric command lines across a dedicated wireless telemetry bridge, the controller receives real-time coordinate strings, implements micro-stepping adjustments, and drives the system tool-head with high geometric repeatability. Furthermore, this structural configuration offers diverse modification opportunities; by replacing the base marking pen with alternative tool assemblies—such as low-power semiconductor laser diodes, high-torque micro-spindle drills, or heated material extruders—the system transforms into a functional desktop laser engraver, small PCB milling unit, or an additive 3D printer [2, 9].

2. System Block Diagram and Functional Sub-Systems

The functional operation of the developed wireless mini CNC plotter is divided into two distinct architectural segments: the host transmitter workstation and the decentralized receiver controller unit. This dual-stage layout separates intensive vector processing tasks from real-time physical motor control, maintaining an uninterrupted data stream and stable wireless communications.

2.1 Transmitter Workstation Layout

The transmitter configuration handles vector graphics parsing, path interpolation, and wireless sequence scheduling. Figure 1 represents the block diagram of the transmitting side of the mini CNC plotter. The operational steps proceed as follows:

- a. Vector Path Formulation: The source design file (such as a geometric drawing, structural outline, or custom font) is imported into an open-source vector editing framework (Inkscape) to organize visual lines into a unified path coordinate matrix.
- b. Numerical Code Compilation: The arranged vector shapes are processed and compiled into sequential alphanumeric lines (G-code data) detailing exact coordinate coordinates, operating feed speeds, and vertical pen states.

c. Control Interfacing and Execution: The compiled G-code files are managed through an open-source serial communication interface ('Sketch It') that sequences and monitors data delivery to the system's active communications port.

d. Telemetry Transceiver Interfacing: Because commercial computer terminals lack built-in low-power radios, a transceiver interface bridge (such as a MAX232 logic level shifter or an integrated USB-to-UART converter) matches the computer's serial outputs with an external Zigbee transmission module.



Figure 1 - Block diagram of the transmitting side of the mini CNC plotter

2.2 Receiver Subsystem Architecture

The remote receiving platform captures wireless coordinate packets, decodes programmatic commands, and manages electrical power distribution across the three-axis motor assembly. Figure 2 represents the block diagram of the receiving side of the mini CNC plotter. The receiver operations proceed through the following hardware links:

a. Wireless Signal Acquisition: An on-board client ZigBee receiver catches incoming IEEE 802.15.4 telemetry packets from the transmitter workstation and passes the clean serial character stream to the master microcontroller.

b. Microcontroller Central Processing: An Arduino development board serves as the central control unit, hosting localized interpreter firmware that parses incoming data bytes into real-time multi-axis step patterns.

c. Planar Axis Actuation (X-Y Axis): Two-dimensional surface adjustments are executed by dual bipolar stepper motors driven by an integrated L293D dual H-bridge motor driver board. Stepper Motor 1 actuates the primary horizontal carriage assembly (X-axis), while Stepper Motor 2 translates the secondary vertical mechanical platform (Y-axis).

d. Vertical Pen Elevation Actuation (Z-axis): Vertical tool-tip displacement is governed by a micro servo motor that lifts or lowers the pen marker based on path state requirements.

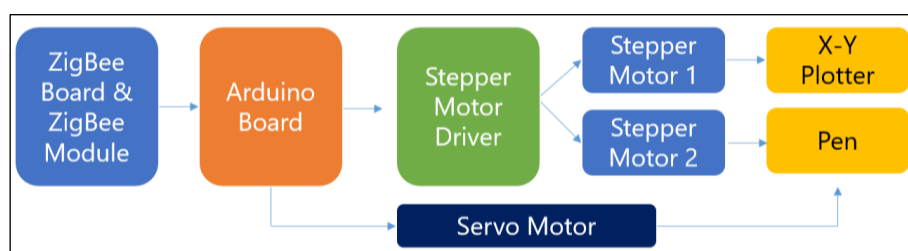


Figure 2 - Block diagram of the receiving side of the mini CNC plotter

3. Hardware Specifications and Component Design

To fulfil the low-cost design objectives of the system, every component was selected based on strict criteria balancing low current consumption, wide open-source community support, and reliable hardware performance.

3.1 Stepper Motors

The primary linear transport axes utilize high-precision discrete step motors to achieve reliable repeatability without relying on costly closed-loop encoder feedback loops [10]. These components use internal electromagnetic coils arranged symmetrically into distinct phase groupings [11]. When digital step pulses are applied sequentially to these coils, the internal permanent magnet rotor turns by fixed angular segments known as step angles. The translation system converts these digital microcontroller pulses directly into linear leadscrew rotations, precisely sliding the pen tool-head to matching coordinates along the X and Y planar axes [5].

3.2 Servo Motors

Unlike continuous step motors, the vertical Z-axis mechanism uses a compact micro servo motor to control tool elevation. The servo unit contains a miniature internal DC motor, a gear-reduction assembly, a position-sensing variable resistor potentiometer, and an integrated feedback control chip [12]. The angular orientation of the output arm is governed via Pulse Width Modulation (PWM) signals, where the width of the incoming microsecond pulse directly commands the output shaft angle [13]. By altering these PWM widths, the microcontroller can quickly lift the pen to skip drawing zones or drop it down onto the substrate to draw continuous vector lines.

3.3 ZigBee Protocol Telemetry Modules

Wireless communication uses ZigBee modules designed to manage low-power personal area network grids using small digital radios [14]. Operating over mesh topology architectures, these transceivers offer excellent link stability and low latency for small data packet sizes. Under standard test environments, these modules communicate reliably across ranges from 10 to 100 meters [14, 15]. This hardware alternative delivers lower overhead, reduced power consumption, and simpler development cycles than equivalent consumer protocols like Bluetooth or Wi-Fi.

3.4 Arduino Microcontroller Platform

The processing core uses an open-source ATmega328P microcontroller board. The board features 14 digital input/output lines (including multiple PWM outputs), 6 independent analogue inputs, a 16 MHz on-board ceramic resonator clock, a hardware USB connection interface, an ICSP header, and an external hardware reset button [16]. The processor reads data packets across wireless ports, processes coordinate paths using local firmware, and commands external motor shields. The device accommodates dual-input power architectures, running via standard 5V USB

connections or an unregulated external DC power jack supporting inputs from 6 to 20 volts.

3.5 L293D Dual H-Bridge Motor Driver

Because microcontroller pins cannot supply enough current to drive inductive motor coils directly, an integrated L293D driver IC is added to the system [16]. This 16-pin monolithic integrated chip features dual four-channel high-current H-bridge drivers capable of delivering bidirectional control currents to inductive loads. It enables the main microcontroller to command two distinct DC or stepper motors simultaneously by toggling logic pins, dictating precise rotation direction and speed.

4. Software Architecture and Programming Environment

The software framework relies entirely on open-source software tools to convert digital graphics files and stream real-time machine codes to the plotter hardware.

4.1 Inkscape Vector Graphic Engine

Inkscape serves as the primary graphic design package for generating vector paths, technical drawing blueprints, and structural layouts. Standard bitmap formats (.PNG, .JPG) are processed using internal edge-detection tracing algorithms to generate clean vector lines [17]. A dedicated G-code tools extension then samples these vector lines, maps them to physical dimensions, and outputs standard coordinate text files containing spatial movement paths (G0 rapid positioning and G1 linear vector interpolation instructions) [8].

4.2 Processing Interface Software ('Sketch It')

The 'Sketch It' control package was developed within the open-source Processing development environment to function as the system's primary computer-hosted control dashboard [18]. This utility reads compiled G-code text strings line by line, verifies formatting syntax, and regulates the data pipeline across the wireless communication link. The operator opens the interactive console, presses 'p' to map the active serial port, and engages the transmission script by pressing 'g' to begin streaming coordinates to the remote receiver platform.

5. System Methodology and Operational Working

The integrated workflow requires systematic interaction between software data generation, wireless data streaming, and physical motor actuation. When data streaming begins, power flows to the main microcontroller via regulated lines, and the remote ZigBee module maintains a stable connection with the host computer terminal. As the Processing software sends coordinate strings, the client ZigBee radio parses the RF packets and pushes incoming characters to the Arduino hardware buffer [15]. The internal interpretation firmware extracts the numeric values for the X, Y, and Z axes.

The microcontroller translates these coordinates into active control sequences, sending them to the CNC shield and motor driver circuits to step the motors in precise order [11]. The structural displacement follows a standard Cartesian coordinate space. Bipolar stepper motors turn internal lead screws to slide the carriage smoothly left or right (X-axis) and forward or backward (Y-axis). Concurrently, the servo motor responds to vertical adjustment commands, rotating its output arm to lift or lower the pen tool-head (Z-axis) [13]. This distributed motor control achieves high spatial plotting accuracy, allowing the miniature tool-head to draw complex geometric artwork on flat substrate mediums.

6. Future Scope and Scalability Analysis

The open-source design of this wireless plotter offers exceptional flexibility for custom modifications and industrial tool scaling:

a. Laser Engraving Subsystem: Replacing the mechanical pen assembly with a high-intensity semiconductor laser diode transforms the unit into a low-cost desktop laser engraver capable of cutting or branding organic sheets, polymers, and thin wooden substrates [2].

b. Sub-Miniature Mechanical Milling: Mounting a high-RPM miniature DC spindle drill allows the system to function as a compact prototyping mill for etching industrial circuit paths directly onto copper-clad PCB boards [5].

c. Additive Manufacturing Expansion: Upgrading the vertical Z-axis with a continuous stepper motor and mounting a heated plastic extruder or 3D printing pen transforms the architecture into an affordable 3D printer for fabricating structural prototypes [19].

7. Experimental Validation and Hardware Prototype

Physical performance tests were performed to verify path accuracy and assess wireless signal quality over varying distances [3]. The prototype assembly was constructed within a durable enclosure housing the core electronic boards, motor drivers, and wireless transceivers [20]. Table 1 provides the experimental validation metrics and operating specifications of the wireless mini CNC plotter

Table 1 – Experimental validation metrics and operating specifications of the wireless mini CNC plotter

Parameter Metric Specification	Measured Experimental Value
Operational Envelope Volumetric Dimensions (X * Y)	40 mm * 40 mm
Core Wireless Communication Protocol Standard	IEEE 802.15.4 (ZigBee)
Line Tracer Repeatability Deviation Range	±0.15 mm
Continuous Transmission Stability Range (Indoor Environment)	Up to 35 meters
Input Logic Shield Distribution Supply Power	12V DC System Input

The hardware prototype proved highly effective at reproducing detailed vector paths without suffering from signal drops or command buffer overflow errors [3, 14].

8. Conclusion

This research demonstrates the design and testing of an affordable, portable, wireless three-axis mini CNC plotter. While conventional industrial CNC machinery remains expensive, difficult to maintain, and reliant on professional machine operators, this prototype offers an accessible alternative. Combining an integrated ATmega328P microcontroller with an open-source vector graphics pipeline creates a reliable digital drawing system. Incorporating a low-latency ZigBee wireless network removes standard cable length limitations, allowing users to safely operate and monitor the machine from long workshop distances. Experimental test results confirm steady tool path tracking and clean layout replication, validating this architecture as an excellent foundational platform for open-source manufacturing and educational lab prototyping.

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