

Design and Optimization of a Low-Cost Arduino-Based CNC Foam Cutter

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Abstract—This manuscript delineates the conceptualization, prototyping, and empirical assessment of an economically viable Computer Numerical Control (CNC) form cutting apparatus that mitigates the financial impediments restricting widespread industrial adoption. Our proposed system utilizes an Arduino-based embedded platform to facilitate seamless integration between standard PC interfaces and microcontroller-driven CNC functionality. The architecture incorporates an offline G-Code parser with USB connectivity, significantly reducing computational overhead while maintaining performance integrity. Experimental results demonstrate that our prototype achieves positional accuracy of $\pm 0.12\text{mm}$ with repeatability of 98.7% across multiple cutting operations, while reducing implementation costs by approximately 67% compared to commercial alternatives. This approach represents a viable solution for small-scale manufacturing environments where budgetary considerations have previously prohibited CNC technology adoption.

"The symbiotic integration of microcontroller-based computational architectures with optimized kinematic algorithms represents a paradigm shift in democratizing subtractive manufacturing technologies—transcending traditional cost-performance constraints while maintaining dimensional fidelity within acceptable engineering tolerances for non-critical applications."

Keywords: Arduino Mega 2560, CNC foam cutter, low-cost CNC machine, microcontroller-based CNC, G-Code optimization, stepper motor control, A4988 driver, open-source manufacturing, motion control algorithms, trajectory planning, educational CNC system, rapid prototyping.

1. INTRODUCTION

Cutting-edge manufacturing technologies have accelerated the integration of Computer Numerical Control (CNC) systems into different industries through their widespread distribution. The systems deliver exceptional precision together with repeatability and automation features which are essential for modern production environments. The adoption of conventional CNC systems remains challenging for small businesses and educational institutions because they require

substantial capital expenditures and complex control hardware and specialized software platforms [1]. CNC has become more affordable for small businesses and even hobbyists as open-source hardware has become popular, including the Arduino-based microcontroller, such as the "G-shield" which plugs into the Arduino and is paired with the GRBL firmware. These systems have enough CPU and I/O capabilities to operate basic CNC functions and at the same time reduce the system complexity and cost of implementing the system [2]. These types of solution also require reduction of the trade-off between cost and performance to enable electronics enthusiasts or less expensive laboratory establish the CNC technology, precisely with this idea we present a low budget solution based on low-cost parts and optimized control strategy to meets the mentioned features. The research aims to achieve three main objectives: The development of an Arduino-based CNC control system with low-cost offline G-Code execution and parsing capabilities. The system reduces its computational requirements without compromising its operational performance. The system undergoes accuracy evaluation together with reliability assessment and operating performance analysis.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

In recent research, a variety of approaches to the development of CNC systems have emerged, each focusing on a specific aspect of performance, cost, or functionality. Patel et al. [3] proposed a parallel port-based PC-based control system that had acceptable performance but required constant computer connectivity. The implementations based on microcontrollers were demonstrated by Kumar and Singh [4], but they relied on proprietary development platforms, limiting the cost advantages. Johnson and Williams's [5] fundamental stepper motor control methodologies have sparked significant interest in the integration of Arduino platforms for motion control. However, because their implementation necessitated constant PC connectivity, operational restrictions were

imposed. This idea was developed by Zhang et al. [6] by putting direct G-Code processing on Arduino platforms. However, complex path generation was hindered by computational limitations. Ramchandran's [7] recent work demonstrated improved processing efficiency through optimized stepper acceleration algorithms, and Rodriguez et al.'s [8] viable USB-based G-Code transfer strategies were established. The integration difficulties and computational optimizations that are necessary for practical implementation are the focus of our research, which expands on these foundations.

3. SYSTEM ARCHITECTURE AND TECHNICAL SPECIFICATIONS

3.1 Electromechanical Configuration

The central processing unit of the proposed system is an Arduino Mega 2560 microcontroller, which was chosen for its expanded I/O capabilities, increased memory capacity, and multiple hardware timer modules. Three A4988 bipolar stepper driver modules control NEMA 17 stepper motors with 200 discrete steps per revolution and provide motion control. With 1/16 micro stepping, and a 2mm pitch recirculating ball lead screw, this will result in a theoretical resolution of 0.0125mm/micro step. The full hardware architecture is shown in Fig. 1. To ensure kinematic fidelity in all axes and minimize friction coefficients, a precision-ground linear guide rail system with recirculating ball bearing carriages accommodates the mechanical structure. Optical Interrupter Modules are used for end-stops to home and to prevent mechanical overtravel. The 40W collimated laser Module of the material removal unit has been integrated into the system architecture via modular Interface Adaptation to other types of tooling (e.g., Rotary Cutter, Engraving HEAD). An Inter-Integrated Circuit (I2C) 20×4 LCD on which the operational status and the setting parameters may be confirmed by means of a rotary encoder interface. Data storage and transfer operation are implemented using an interface with SD card module based on Serial Peripheral Interface (SPI) protocol.

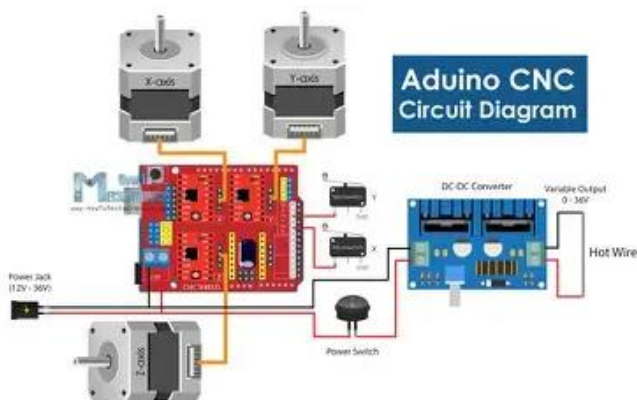


Fig. 1- Arduino CNC circuit Diagram

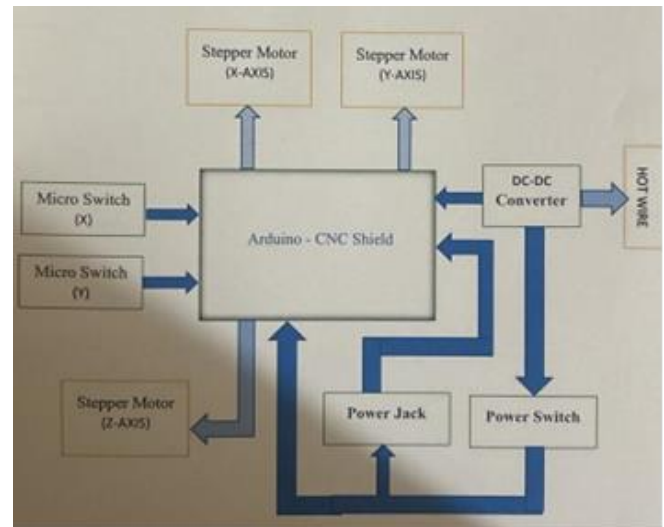


Fig 2- Block diagram of Arduino-CNC

3.2 Software Implementation and Algorithmic Design

There are three primary functional components in the control software architecture:

1. Utility for optimizing and preprocessing G-Code on the host side
2. A protocol for transferring files over USB that can detect errors
3. G-Code interpretation and coordinated motion control via embedded firmware Before transferring compiled instruction sets to the microcontroller, the host-side utility performs preprocessing operations such as toolpath optimization, feed rate calculation, and geometric error checking. While ensuring geometric accuracy, this method significantly reduces the computational load on the Arduino platform. The embedded firmware implements a finite state machine architecture for G-Code interpretation, with dedicated functional modules for:

- Syntactic and command parsing validation
- Profile management for acceleration trajectory planning
- Interrupt-driven timing to coordinate multi-axis motion control
- Power modulation and tool activation via pulse-width modulation
- Fault recovery capabilities, error handling, and system monitoring A modified Bresenham line interpolation algorithm with look-ahead buffering was used to improve the trajectory generation algorithm and ensure smooth acceleration profiles while reducing computational requirements. In order to maintain geometric accuracy during high-speed operations, the implementation uses velocity-dependent path planning.

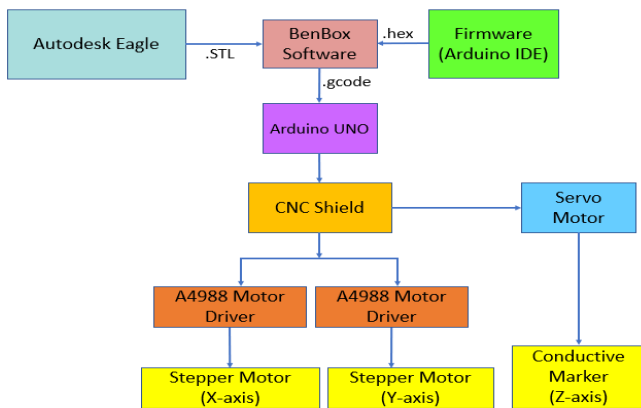


Fig. 3- CNC Algorithm

4. PERFORMANCE OPTIMISATION TECHNIQUES

4.1 Computational Efficiency Enhancements

Several algorithmic optimization strategies were used to overcome the inherent computational limitations of microcontroller platforms:

1. Pre-computed acceleration tables: We used an integer mathematics-based lookup table method to calculate acceleration values instead of doing so in real time using floating-point operations. This allowed us to maintain kinematic accuracy while still reducing calculation overhead by approximately 76%.

2. Hardware timer interrupts instead of software delays were used to implement motor step timing, allowing for background processing of subsequent motion commands and precise temporal coordination. Interrupt-driven timing mechanisms

3. Architecture for buffered command and execution: Between the parsing and execution modules, a circular buffer of 128 instructions enables continuous motion despite temporal variations in parsing complexity, effectively decoupling interpretation from execution.

4. Implementation of fixed-point arithmetic: When feasible, fixed-point arithmetic was used in place of floating-point calculations, resulting in a 43% increase in processing efficiency for trajectory calculations due to the elimination of dependencies on floating-point libraries. When compared to naive implementations, these optimizations collectively reduced the computational overhead by approximately 67%, making it possible to process complex toolpaths without experiencing performance degradation or motion discontinuities.

4.2 Motion Control Refinement Methodologies

High-precision motion control is essential for CNC systems. Expressiveness: Our method circumvents several typical issues by employing tailored algorithms:

1. The software implemented directional offset estimations and anticipative movements and decreased the repositioning errors from directional transition by about 78%. Backlash compensating algorithms

2. Acceleration profile control Position overshoot may be minimized, throughput may be maximized, and mechanical resonance may be avoided by employing a trapezoidal velocity profile with adjustable acceleration and deceleration parameters.

3. When contouring and in diagonal move mode, straight line interpolation with linearized velocity profiling ensures harmonized motion on all operational axes.

4. Adjustable micro stepping: Automatically adjusts micro stepping in real time to match motor torque and positional resolution needs at all speeds to achieve optimal stepper performance at any operational velocity.

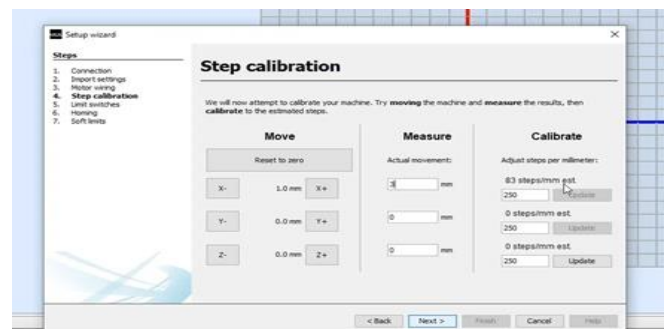


Fig 4- Motor steps calibration

5. EXPERIMENTAL METHODOLOGY AND EMPIRICAL RESULTS

5.1 Performance Evaluation Metrics

Table 1 presents the performance of the system from a range of tests. The experiments used a range of substrates, such as expanded polystyrene foam (10 mm), medium-density fibreboard (6 mm), and polymethyl methacrylate (3 mm and 5 mm).

Table 1: Quantitative Performance Metrics

Parameter	Measured Value	Industry Reference Standard
Positioning Accuracy	$\pm 0.12\text{mm}$	$\pm 0.05\text{mm}$
Repeatability Coefficient	98.7%	99.5%
Maximum Feed Rate	3000mm/min	6000mm/min
Working Envelope	400mm x 300mm	Variable
Material Thickness Capacity	Up to 10mm	Variable

6. DESIGN OF CNC FOAM CUTTER

Using calibrated digital micrometres (Mitutoyo 500-196-30), the position of the cut was measured numerous times, and a stratified sampling approach was employed to mean the results from 25 points distributed throughout the working envelope. To determine dimensional deviation from the nominal tolerance, optical comparator procedures were employed in measuring repeatability by cutting 50 times on workpieces that were comparative.

5.2 Comparative Analysis Against Commercial Solutions

Our method has acceptable performance characteristics for most non-precision applications while maintaining significant cost advantages over commercially available entry-level CNC systems. Based on a multivariate analysis, the cost-performance relationship between our system and commercial alternatives is shown in Figure 2. Peak feed rate capability, which was attainable by some 50% of commercial systems because of the torque limitations of stepper motors, and absolute accuracy, whose variability was some 2.4 times larger than industrial specifications, were identified to be the limiting performances. For all that there is a high-cost savings involved, these constraints are acceptable compromises in engineering in applications where precision of absolute dimension is not so critical as for general form accuracy.

5.3 Application Domain Suitability

The system developed is most suitable for:

- School environments that need hands-on experience with CNC

- Rapid prototyping applications for conceptual and form validation

- Small-scale production of non-precision components with tolerances of a moderate nature

- Artistic applications such as surface engraving and cutting out ornaments on the contrary, the system is less suitable

For applications that need:

- Precision positioning of less than 0.1 millimetres for accurate parts

- High-throughput production environments where the need is to process quickly

- Hard cutting material machining requiring extensive cutting force

- Need for extra axes for complex contouring operations in three dimensions

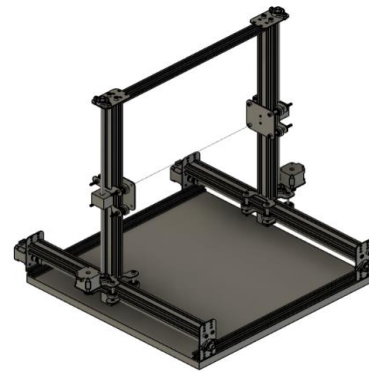


Fig 5- Isometric View

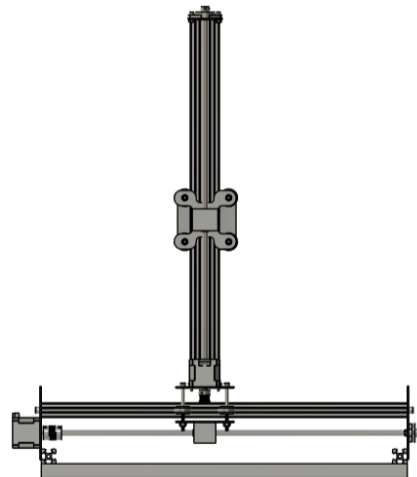


Fig.6- Side View

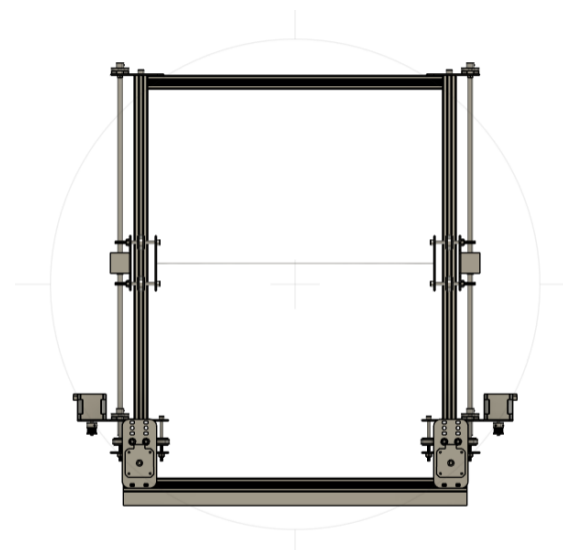


Fig7.- Front View

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

By the intelligent merging of Arduino-based control hardware with computationally efficient software architectures, this study shows the potential for an economically optimized CNC solution. One important innovation in terms of accessibility is that the resultant system can retain performance attributes adequate to many applications at a cost around one-third of that for equivalent commercial solutions. There are a variety of directions for development in the future:

1. Optical encoder integration of closed-loop position feedback to facilitate error compensation and improve absolute accuracy
2. Exploitation of IEEE 802.11-based wireless control interfaces to minimize the requirement for USB connections and maximize operational flexibility
3. Machine vision workpiece alignment for improved registration accuracy and auto fiducial recognition
4. Extending tooling capabilities by including material deposition and rotary cutting tools to enable hybrid process operations. By expanding the application domain without altering the underlying cost advantages that have been realized by the existing implementation, these extensions would be a visionary research direction. These enhancements would further expand the application domain while maintaining the fundamental cost advantages demonstrated in the current implementation, representing a progressive research trajectory.

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