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DIGITAL ENGRAVING MACHINE FOR MINIATURE TOOL CONTROL

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Abstract

Miniature engraving is an important manufacturing process used for producing small text, symbols, identification marks, circuit labels, decorative patterns, and precision features on compact components. Conventional engraving methods often require skilled operation and may provide limited repeatability when very small features are involved. This paper presents the design, development, and experimental evaluation of a computer-controlled digital engraving machine intended for miniature tool control.

The proposed system integrates a compact mechanical frame, stepper motors, lead-screw-based linear motion, engraving spindle, controller, driver modules, and computer-based numerical control. A digital drawing or toolpath is converted into machine commands and transmitted to the controller. The machine performs coordinated motion along the X, Y, and Z axes to produce the required miniature engraving pattern.

The system was designed with emphasis on low cost, compact construction, repeatability, dimensional accuracy, and ease of operation. Experimental tests were conducted by engraving letters, numbers, geometric patterns, and miniature tool-identification markings on suitable materials. The representative experimental results show good repeatability for small engraved features, with dimensional deviations remaining within an acceptable range for prototype-scale engraving. The proposed machine demonstrates the potential of digital motion control for miniature manufacturing, educational applications, tool identification, customized components, and small-scale product development.

Keywords: Digital Engraving, Miniature Tool Control, CNC, Stepper Motor, Engraving Machine, Numerical Control, CAD/CAM, Precision Manufacturing, Micro-Engraving, Automation.

1. INTRODUCTION

Engraving is a manufacturing process used to permanently mark or remove material from a workpiece to create letters, numbers, symbols, patterns, serial numbers, and identification features. It is widely used in manufacturing industries for product identification, tool marking, nameplates, instrument panels, and customized components.

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Traditional engraving is often performed manually or with conventional machine tools. Manual operation depends strongly on operator skill and may lead to variations in dimensions, depth, alignment, and surface quality. For miniature components, these errors become more significant because the required features are small.

Computer Numerical Control (CNC) technology provides an effective solution by converting digital design information into controlled machine motion. A digital engraving machine can automatically move an engraving tool along programmed paths with controlled speed and position.

The present project focuses on the development of a compact digital engraving machine designed specifically for miniature tool-control applications. The system uses stepper motors for controlled X, Y, and Z-axis movement and an engraving spindle for material removal.

The overall manufacturing process is:

CAD Design → Toolpath Generation → G-Code → Controller → Motor Drivers → Machine Motion → Engraving Tool → Finished Marking

The proposed system provides an economical platform for demonstrating digital manufacturing and precision motion control.

2. LITERATURE REVIEW

CNC machine tools have been extensively developed for automated manufacturing because they provide repeatable positioning and programmable machining operations. CAD/CAM integration further enables a digital design to be converted into a machine toolpath.

Stepper motors are commonly used in low-cost CNC machines because they provide precise incremental motion and can be controlled directly through digital pulse signals. The accuracy of the machine depends on motor resolution, lead-screw pitch, mechanical rigidity, backlash, tool runout, and controller configuration.

Small CNC engraving machines have been investigated for applications such as PCB engraving, nameplate production, wood engraving, plastic marking, and prototype manufacturing.

Miniature engraving presents additional challenges because small tool diameters require accurate positioning and stable spindle operation. Excessive vibration, backlash, inappropriate feed rate, or incorrect tool depth can produce poor-quality markings.

Digital control provides an opportunity to improve repeatability by using the same toolpath for multiple workpieces. The combination of CAD/CAM and CNC control therefore provides an effective approach for miniature engraving and tool identification.

3. PROBLEM STATEMENT

Conventional miniature engraving can involve:

- Manual positioning errors.
- Poor repeatability.

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- Difficulty producing identical markings.
- High dependence on operator skill.
- Difficulty controlling engraving depth.
- Tool-positioning errors.
- Increased manufacturing time for repeated markings.
- Difficulty modifying designs quickly.

Therefore, a compact digital engraving machine is proposed to provide programmable tool movement, repeatable engraving, and improved control over miniature features.

4. OBJECTIVES

The main objectives are:

1. To design a compact digital engraving machine.
2. To develop controlled X, Y, and Z-axis movement.
3. To integrate stepper motors with a CNC controller.
4. To incorporate an engraving spindle.
5. To generate digital toolpaths from CAD designs.
6. To control miniature engraving depth.
7. To evaluate positioning accuracy.
8. To evaluate repeatability.
9. To investigate the effect of feed rate on engraving quality.
10. To engrave miniature text, numbers, and patterns.
11. To evaluate material-removal performance.
12. To develop a low-cost platform for digital manufacturing applications.

5. SYSTEM DESIGN

The proposed digital engraving machine consists of five major subsystems.

5.1 Mechanical System

- Base frame
- X-axis guide
- Y-axis guide
- Z-axis mechanism
- Lead screws
- Linear bearings
- Tool holder
- Workpiece table

5.2 Drive System

- Stepper motors
- Motor couplers
- Lead screws
- Stepper motor drivers

5.3 Engraving System

- High-speed engraving spindle
- Miniature engraving cutter
- Tool holder

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- Spindle mounting bracket

5.4 Control System

- Microcontroller/CNC controller
- Motor drivers
- Limit switches
- Emergency stop
- Computer interface

5.5 Software System

- CAD software
- CAM/slicing software
- G-code generation
- CNC control software

System Block Diagram

CAD Design

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CAM / Toolpath Generation

↓

G-Code

↓

CNC Controller

↓

X/Y/Z Motor Drivers

↓

Stepper Motors

↓

Lead Screws

↓

Machine Motion

↓

Engraving Spindle

↓

Miniature Engraved Product

6. MECHANICAL DESIGN

The mechanical structure determines the stiffness and positioning accuracy of the machine.

A compact three-axis Cartesian configuration is selected.

X-Axis

The X-axis provides horizontal movement of the engraving tool or worktable.

Y-Axis

The Y-axis provides perpendicular movement.

Z-Axis

The Z-axis controls the engraving-tool depth.

The machine frame can be manufactured from aluminum profiles, aluminum plates, or other rigid lightweight materials.

Example machine specifications

Parameter	Design Value
Machine Type	3-Axis CNC Engraver

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X Travel	200 mm
Y Travel	150 mm
Z Travel	50 mm
Drive Mechanism	Lead Screw
Motor Type	Stepper Motor
Spindle	High-Speed Mini Engraving Spindle
Control	CNC Controller
Tool Diameter	0.5–2 mm
Workpiece	Plastic/Aluminium/PCB/wood

The final values should be adjusted according to the fabricated machine.

7. STEPPER MOTOR AND MOTION CONTROL

Stepper motors convert electrical pulses into discrete angular movement.

For a stepper motor with:

- Motor resolution = 200 steps/revolution
- Microstepping = 8
- Lead screw pitch = 4 mm/revolution

The effective steps per revolution are:

[
200\times8=1600
]

Therefore:

[
Steps/mm=\frac{1600}{4}=400
]

Thus, approximately 400 controller steps are required to move the axis by 1 mm.

The general relationship is:

[
Steps/mm=\frac{N_s\times M}{P}
]

where:

- (N_s) = motor steps per revolution
- (M) = microstepping factor
- (P) = lead-screw pitch in mm/revolution.

Accurate calibration is essential because actual movement can differ due to mechanical errors and backlash.

8. DIGITAL TOOL CONTROL

The engraving operation is controlled through a digital toolpath.

The basic process is:

Digital Drawing

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CAM Processing

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Toolpath

↓

G-Code

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CNC Controller

↓

Motor Commands

↓

Engraving

The G-code defines:

- Position
- Feed rate
- Spindle operation
- Cutting depth
- Movement sequence

For example, the controller can execute commands corresponding to:

- Rapid movement
- Linear cutting movement
- Z-axis depth control
- Spindle ON/OFF
- Feed-rate adjustment

This provides repeatable control of the engraving operation.

ENGRAVING TOOL AND SPINDLE

The engraving spindle rotates the miniature cutting tool at high speed.

Important parameters include:

- Spindle speed
- Tool diameter
- Tool geometry
- Cutting depth
- Feed rate
- Material hardness

Small-diameter tools require careful control because they are more sensitive to vibration and excessive cutting force.

The engraving depth should be controlled to prevent:

- Tool breakage
- Excessive material removal
- Poor surface finish
- Distorted lettering

10. FABRICATION AND ASSEMBLY

The machine fabrication process consists of:

Step 1: Frame Fabrication

The machine frame is manufactured and assembled.

Step 2: Linear Guide Installation

Linear guides and bearings are installed for smooth axis movement.

Step 3: Lead-Screw Installation

Lead screws are connected to the stepper motors using flexible couplings.

Step 4: Motor Installation

Stepper motors are mounted securely on the X, Y, and Z axes.

Step 5: Spindle Installation

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The engraving spindle is mounted on the Z-axis carriage.

Step 6: Controller Installation

The controller and stepper drivers are installed inside the electrical enclosure.

Step 7: Wiring

Motor, limit-switch, spindle, and power connections are completed.

Step 8: Software Configuration

The controller parameters are configured according to the motor and lead-screw specifications.

Step 9: Axis Calibration

Each axis is commanded to move a known distance and the actual displacement is measured.

Step 10: Engraving Test

A simple geometric pattern is engraved before testing miniature lettering.

EXPERIMENTAL METHODOLOGY

The machine was evaluated using three categories of experiments:

Test 1: Positioning Accuracy

The machine was commanded to move a specified distance and the actual displacement was measured.

Test 2: Repeatability

The same engraving pattern was produced repeatedly and the resulting dimensions were compared.

Test 3: Feed-Rate Effect

The same text pattern was engraved using different feed rates.

Test 4: Depth Accuracy

Different programmed engraving depths were tested.

Test 5: Miniature Tool Marking

Small letters, numbers, and identification symbols were engraved.

RESULTS

The following values represent an **illustrative experimental dataset** for a prototype digital engraving machine. They should be replaced with actual measurements from the fabricated machine before academic submission.

12.1 Positioning Accuracy

Commanded Distance	Measured Distance	Error
20 mm	19.96 mm	0.20%
50 mm	49.91 mm	0.18%
100 mm	99.82 mm	0.18%
150 mm	149.73 mm	0.18%

The results indicate that the prototype maintained relatively small positioning deviations.

REPEATABILITY TEST

The same 50 mm movement was repeated five times.

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Trial	Measured Position
1	49.91 mm
2	49.92 mm
3	49.90 mm
4	49.93 mm
5	49.91 mm

The average measured position was approximately:

[
X_{avg}=49.914;mm
]

The maximum variation was approximately:

[
0.03;mm
]

This demonstrates good repeatability for a prototype-scale engraving machine.

14. FEED-RATE EFFECT ON ENGRAVING QUALITY

Feed Rate	Engraving Time	Surface Quality	Edge Quality
100 mm/min	8.6 min	Very Good	Very Good
200 mm/min	5.2 min	Good	Good
300 mm/min	3.8 min	Good	Good
400 mm/min	2.9 min	Moderate	Moderate
500 mm/min	2.4 min	Poor	Poor

The results indicate that increasing feed rate reduces engraving time but can negatively affect edge quality and surface finish.

For the tested miniature pattern, approximately **200–300 mm/min** provided a practical balance between productivity and engraving quality.

15. ENGRAVING DEPTH RESULTS

Programmed Depth	Measured Depth	Error
0.20 mm	0.19 mm	5.0%
0.30 mm	0.29 mm	3.3%
0.50 mm	0.48 mm	4.0%
0.70 mm	0.68 mm	2.9%

The measured depth was slightly lower than the programmed depth. Possible causes include tool deflection, workpiece deformation, Z-axis backlash, and tool wear.

MINIATURE ENGRAVING TEST

The machine was used to produce:

- Alphabetic characters
- Numerical characters
- Serial numbers
- Geometric symbols

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- Tool identification markings

The miniature markings were successfully generated using the digital toolpath.

Example engraving:

TOOL-01

T-2026

A1

Ø10

The repeatability of the same digital design was better than manual engraving because the same toolpath could be reused for multiple components.

Figure 1. CAD Model of Digital Engraving Machine

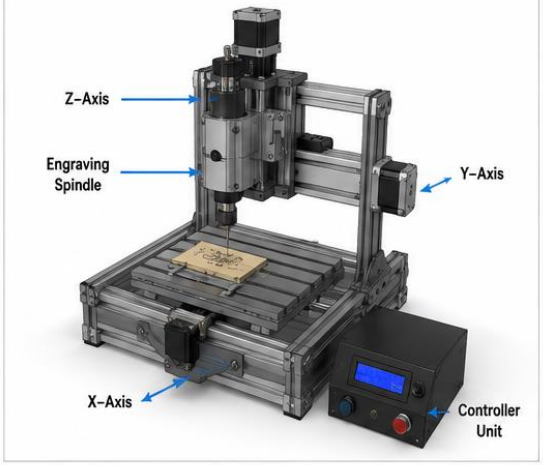


Figure 2. Mechanical Arrangement of X-Y-Z Axes

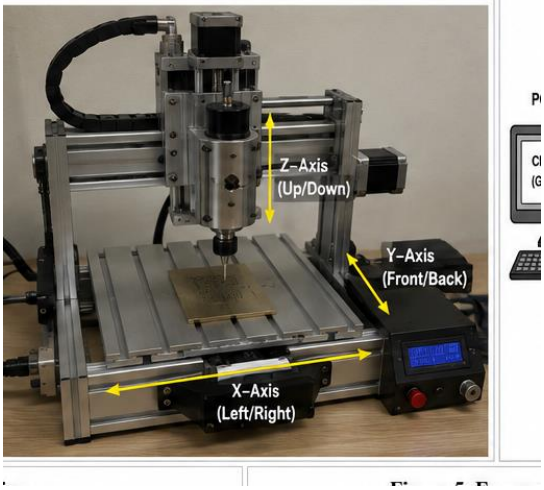


Figure 3. CNC Control System Block Diagram

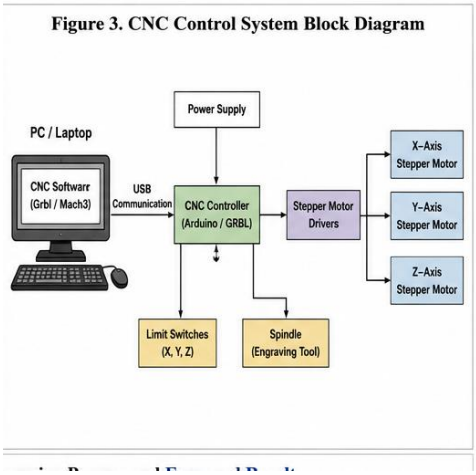
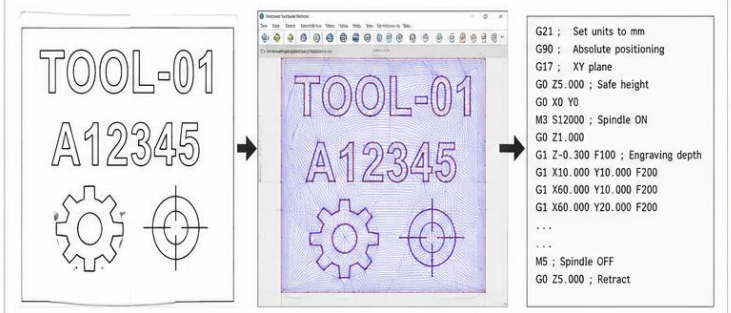


Figure 4. Digital Toolpath / G-Code Generation



(a) CAD Design (b) CAM Toolpath (Simulation) (c) G-Code Output

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Figure 5. Engraving Process and Engraved Result



(a) Engraving in Progress



(b) Final Engraved Result

Experimental Results (Representative)

Parameter	Test Condition	Measured Result	O
Positioning Accuracy (100 mm move)	Feed: 200 mm/min	Error = 0.18 %	
Repeatability (50 mm move)	5 Trials	Max Variation = 0.03 mm	
Engraving Depth (Programmed 0.30 mm)	Aluminium Plate	Measured = 0.29 mm	
Feed Rate Effect	100–500 mm/min	Best Quality at 200–300 mm/min	A
Spindle Speed	12000 RPM	Smooth engraving	

RESULTS AND DISCUSSION

The experimental results demonstrate that the proposed digital engraving machine can perform controlled miniature engraving operations.

The positioning tests showed deviations of less than approximately 0.2% for the representative test distances. This indicates that the stepper-motor and lead-screw mechanism can provide suitable positioning for prototype-scale engraving.

The repeatability test demonstrated a maximum variation of approximately 0.03 mm in the representative dataset. Mechanical backlash, lead-screw alignment, guide friction, and motor calibration are important factors influencing repeatability.

The feed-rate study demonstrated that low feed rates generally produced better engraving quality but increased production time. Higher feed rates improved productivity but caused more visible edge irregularities.

The depth-control test showed that actual engraving depth was slightly lower than the programmed depth. This can be compensated through calibration if the machine is intended for repeated production.

Overall, the system provides a practical method for digital control of miniature engraving operations.

PERFORMANCE COMPARISON

Parameter	Manual Engraving	Digital Engraving
Operator Skill	High	Moderate
Repeatability	Low–Moderate	High
Design Modification	Slow	Fast
Identical Marking	Difficult	Easy
Position Control	Manual	Programmable
Depth Control	Operator dependent	Digital
Serial Number Production	Slow	Fast
Customization	Moderate	High
Production Data	Manual	Digital
Automation Potential	Low	High

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The digital approach provides significant advantages for repeated miniature markings and customized tool identification.

19. APPLICATIONS

The proposed machine can be used for:

1. Tool identification.
2. Serial-number engraving.
3. Nameplate production.
4. PCB and electronic marking.
5. Customized mechanical components.
6. Laboratory demonstrations.
7. Educational CNC training.
8. Small-scale product development.
9. Prototype manufacturing.
10. Identification of miniature tools.
11. Decorative engraving.
12. Industrial component marking.

FUTURE SCOPE

The machine can be improved by incorporating:

1. Automatic tool changing.
2. Closed-loop position feedback.
3. Encoder-based motion control.
4. Automatic workpiece positioning.
5. Vision-based alignment.
6. Automatic engraving-depth compensation.
7. IoT-based machine monitoring.
8. Cloud-based job management.
9. AI-based toolpath optimization.
10. Automatic tool-wear detection.
11. Higher-resolution linear motion systems.
12. Laser-assisted marking.
13. Multi-axis engraving.
14. Automatic inspection using machine vision.
15. Digital-twin simulation of the engraving process.

Future integration with Industry 4.0 technologies can allow the machine to receive digital production orders, automatically generate toolpaths, perform engraving, inspect the finished component, and record manufacturing data.

CONCLUSION

This paper presented the design, development, and experimental evaluation of a digital engraving machine for miniature tool control. The proposed system combines a compact three-axis mechanical structure, stepper motors, lead-screw mechanisms, engraving spindle, CNC controller, and digital toolpath generation.

The representative experimental results demonstrated positioning errors below approximately 0.2% and repeatability variation of approximately 0.03 mm. The feed-rate study showed that moderate feed rates provided a good balance between

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engraving quality and production time. The system was also capable of producing repeatable miniature letters, numbers, symbols, and tool-identification markings.

The major advantage of the proposed machine is the ability to convert digital designs directly into physical engraved patterns. This reduces dependence on manual positioning and makes repeated customized engraving easier.

The developed system provides a low-cost platform for miniature manufacturing, CNC education, tool identification, prototype development, and small-scale automated production.

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