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Research and development of CNC machine prototype for laser cutting and engraving

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Original article

Abstract

Technological development of lasers has evolved rapidly. Lower-cost, highly reliable fibre lasers are now used to accurately engrave, cut, and mark components. The widespread use of laser across various industries has contributed to improvements in process quality and efficiency. CNC machines, which operate using computerised numerical control systems, are capable of performing a wide range of manufacturing tasks, including cutting and marking. Arduino, an open-source electronics platform, provides an accessible foundation for exploring embedded and CNC system design. This study presents an approach to improving laser control throughout its operational cycle. Control is achieved through end sensors, primarily at the initial stage of processing and information calibration. The main objective of the research is to design, construct and test of a low-cost CNC prototype for laser cutting and engraving based on the Arduino platform.

Keywords

- laser cutting
- CNC
- modeling
- prototyping

Authors contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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None declared.

Introduction

Cutting processes have always been an integral part of the manufacturing industry. There are varying methods of cutting metal, each with its own capabilities, limitations, and costs. Among these, laser technology an acronym for Light Amplification by Stimulated Emission of Radiation has become one of the most transformative tools in modern industry. Continuous improvements in laser power, precision, and efficiency have made it an indispensable part of contemporary production processes.

Today, lasers are employed in a variety of industrial applications, including drilling, cutting, welding, heat treatment, marking, and annealing, the latter two modifying the surface characteristics of materials. Moreover, additive manufacturing technologies such as Selective laser melting (SLM) and Selective Laser Sintering (SLS) utilize laser energy to fabricate parts layer by layer from powdered materials. These methods are redefining how components are designed and manufactured, enabling unprecedented levels of customization and complexity.

The integration of laser engraving and cutting machines into manufacturing operations has had a profound impact on the industry. Key benefits include increased quality, efficiency and productivity, enhanced design and customization, cost reduction and waste minimization, versatility and diversification, improved safety and environmental impact [1]. Complementary to laser systems, CNC (Computer Numerical Control) machines, which are capable of executing various manufacturing operations such as cutting, marking and engraving have also had a significant influence on industrial efficiency, product quality and flexibility. Consequently, CNC technology is increasingly used in a wide range of sectors. For example, in the aerospace industry, CNC systems are essential for producing components with extremely tight tolerances and complex geometries [2].

CNC systems operate primarily in two programming modes: incremental and absolute. In incremental mode (G91), coordinates are defined relative to the previous point, whereas in absolute mode (G90), positions are referenced from a fixed origin. These approaches underpin the two principal categories of CNC control: point-to-point and continuous-path programming. The most widely used programming convention is the word-address format, which combines preparatory and miscellaneous codes to define each tool movement [3].

Recent advances in open-source hardware have further democratized CNC research and prototyping. Platforms such as Arduino provide a cost-effective entry point for developing embedded control systems, allowing students and engineers to experiment with real-time control, motion planning, and sensor integration. In this context, the use of laser modules with Arduino-based CNC systems represents a powerful and educationally valuable approach to studying modern manufacturing automation.

Materials and methods

This section outlines the development process of a CNC prototype for laser cutting and engraving, built around an Arduino Uno microcontroller. The project requirements were clearly defined and reasonably straightforward, without unnecessary technological or mathematical complexity. However, the implementation process was relatively challenging and required precision and technical skill. The primary objective was to design a low-cost educational device that aligns with training programs in higher education institution (HEI), providing both theoretical understanding and hands-on experience in mechatronics through accessible examples. The project tasks included 3D printing, component design, electronic testing, mechanical assembly, software setup, and firmware configuration.

Laser Cutting is the technology which uses a laser to vaporize and carve away excess materials. While laser used to primarily be used in manufacturing it is now utilized in various industries.

Advantages: can handle complex cuts and has high accuracy.

Disadvantages: material type restrictions, material thickness restrictions, required edge clean-up, and high heat inputs. [4]

The operation of CNC machines is based on a specifically designed software program, which contains detailed instructions regarding the geometry of the object to be produced and the necessary machining process. This program is processed by the machine's numerical control, which translates the instructions into electrical signals sent to the machines' motors and actuators. Consequently, it guides the movements of the tools and machining devices. This means that the instructions determine everything from the position and speed of the tool to the depth of cut. [5]

This system combines two technologies: a plotter, which uses the same principles as CNC machines, and laser cutting. The design is quite simple, with the pencil-based effector replaced by a laser. The general schematic diagram of the module connection is shown in the figure, see Figure 1.

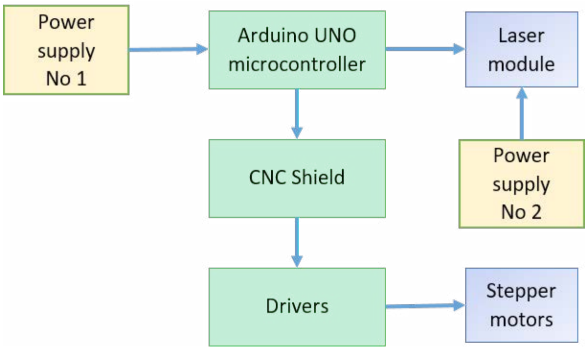

Figure 1. Schematic diagram of the module connection

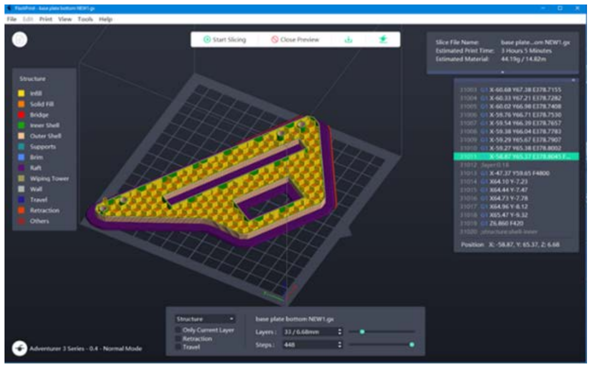

Figure 3. Flash Forge software

3D Printing

To initiate the project, the required components were acquired, and several custom parts were designed and 3D printed. The model files were obtained from Thingiverse or created in Autodesk Inventor. The geometries were verified using a 3D viewer before printing (Figure 2).

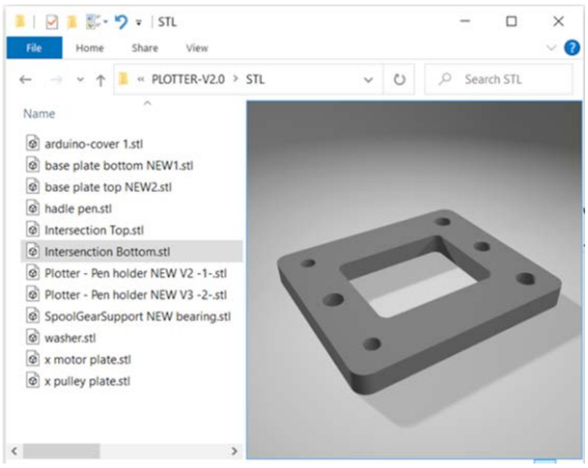

Figure 2. Example of the 3D model in STL format

The 3D models were then processed using slicer software such as Flashforge or Orca Slicer (see Figure 3). The models represented parts specifically designed for the plotter assembly.

Temperature-resistant PLA plastic was primarily used for 3D printing. Certain parts required modification in Autodesk Inventor and were printed using PETG material (Figure 4). The slicer software generated the G-code for printing, and a honeycomb structure was applied within the parts to improve strength and reduce material use (Figure 3).

Figure 4. The 3D printed parts that were updated in Inventor software

Stepper motors

The mechanical movement along the axes was achieved using stepper motors and a belt drive. Radial ball bearings were employed, with only two axes (X and Y) implemented since the laser head does not move vertically, eliminating the need for a Z-axis. The X–Y belt assembly was tensioned to the required level, and both motors were synchronized.

CNC shield setups

The CNC shield can be powered in two ways:

1. By soldering or crimping an 18-gauge wire to connect the shield to the Arduino Uno.
2. By supplying power directly to the CNC shield through its power connector.

Three jumpers were installed for each stepper driver. In this setup, A4988 stepper drivers were used, with the screw terminal facing away from the push button

Laser module specifications

The laser module used in the prototype had the following specifications:
Model: 20 W Laser Module
Type: compressed spot focusing laser
Optical power: 5.5 W
Electric power: 20 W
Product size: 44 × 138 mm
Focal distance 5 mm
Input voltage & current: 12V, 3 A (24V, 3A)
Engraving accuracy: 0.02 mm
Mini focus Spot Size: 0.08 × 0.08 mm
Interface: 3pin (12V, GND, PWN) (24V, GND, PWN)
Cutting depth: 3–4 mm

The laser module was installed as shown in Figure 5.

Figure 5. Laser installation (Next to the laser, a test pattern is visible, which was used to determine the initial calibration of the laser and plotter)

Software installation

To operate the CNC machine, the GRBL firmware was uploaded to the Arduino Uno microcontroller. GRBL enables communication via G-code commands using a host application. Both the pen plotter and the laser version of the device rely on the same Arduino CNC Shield platform, preloaded with firmware and configured with appropriate parameters.

Driver precision and microstepping

The A4988 driver supports microstepping up to 16×, allowing for 3200 steps per revolution (200 × 16). While this theoretically improves positional resolution, excessive microstepping reduces torque and does not significantly enhance accuracy due to mechanical tolerances. For a NEMA17 motor with 200 steps/rev and a 2 mm lead screw pitch, the baseline resolution is 0.01 mm/step. With a GT2 pulley (20 teeth, 40 mm per revolution) and 16× microstepping, the effective precision is approximately 0.0125 mm/step adequate for this prototype [6].

Error determination method

A line is called a straight line of a given length if the deviations of different points of the line from two mutually perpendicular reference planes remain within specified limits. The reference planes are chosen so that their intersection is parallel to the straight line passing between two specified end points. The straightness tolerance of a line is defined as the maximum deviation of the location of points on both sides of the reference line, as shown in the Figure 6 [7].

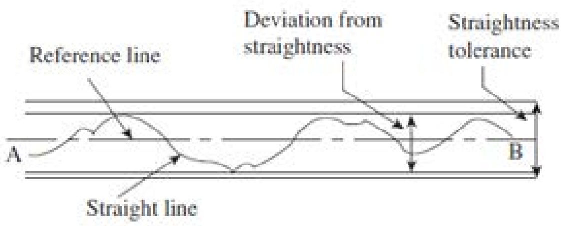

Figure 6. Error detection method. The method determines deviations from the midline

In this experiment, an A4 sheet with a predefined stencil was used to create an ellipsoidal image from the center. The deviations of reference points were measured at fixed intervals [7].

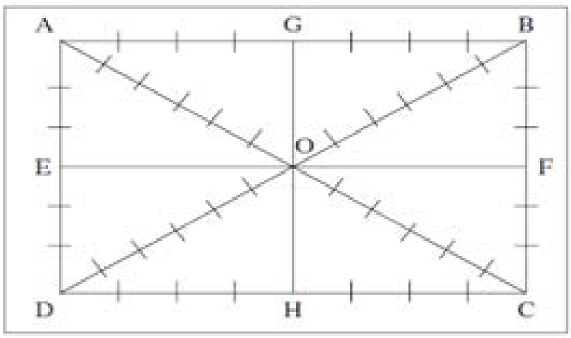

Figure 7. A sheet of material for performing a machine axis calibration test

After applying the image to the plotter, a regular ruler with an accuracy of 0.5 or 0.25 mm can be used to determine the main line distortions on a sheet of calibration material. To calibrate the machine, the drawing (see Figure 7) was used.

For processing the results, it is recommended to use the basic metrology equation $\Delta = R1 - R2$. Where Δ is the difference between two adjacent dimensions R1, R2 for a given image in the drawing, 8 dimensions can be used in four directions at once on all sides, they must be the same, therefore the value of Δ in the ideal case and maximum accuracy should be equal to zero.

After processing all series, and in our case there will be series with different measurement radii. Ideally, every point at every stage of production should be checked. Statistical methods provide a reliable and cost-effective method of quality assurance known as statistical quality control (SQC).

Conclusions

In recent years, significant progress has been made in the development and investigation of direct diode lasers for cutting and engraving applications. As a result, the initial concept of constructing a simple plotter was gradually transformed into the design of a laser-based cutting and engraving system. The individual stages of development did not present major difficulties. On the contrary, they provided a valuable opportunity to examine several theoretical and practical aspects of the process and to identify potential directions for future advancement.

In the context of developing a simple CNC machine, particular attention should be given to the selection of electronic components. Such components should be universal, easily configurable, and user-friendly, while also conforming to the principles of information transparency characteristic of open-architecture systems. Adopting this approach enables the construction of a relatively sophisticated device from straightforward and readily available components.

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