Al-Najah National University

FACULTY OF ENGINEERING AND INFORMATION TECHNOLOGY

Computer Engineering Department

Hardware Graduation Project

CNC System for Wood and Plastic Engraving

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Disclaimer Statement

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Abstract

CNC carving machines play a significant role in modern industries and crafts, particularly in fields such as woodworking, plastic fabrication, and artistic engraving. This project presents the design and implementation of a CNC machine dedicated to carving and engraving on wood and plastic materials with high precision. The system operates on three axes (X, Y, Z) controlled by an Arduino microcontroller integrated with the GRBL Web interface via a serial connection. This interface facilitates essential functions such as defining the carving dimensions, adjusting operational settings, and converting digital designs into G-code instructions for seamless execution.

The project was developed through several phases: starting with the mechanical design of the three-axis structure and base, followed by programming the Arduino controller and testing the axis movements to ensure accuracy. Subsequently, the system was integrated with the GRBL Web platform, enabling users to upload designs, convert them into G-code, and manage the machine efficiently. Final testing focused on achieving reliable communication between hardware and software components to deliver optimal carving performance on both wood and plastic. Unlike conventional CNC systems, this project emphasizes ease of use and adaptability, making it suitable for small workshops, prototyping, and custom artistic production.

Contents

Introduction

Problem Statement

Traditional methods of engraving and cutting on wood and plastic often lack precision, require significant manual effort, and are time-consuming. Existing CNC machines are either expensive or lack user-friendly interfaces that simplify the design-to-production process. There is a need for a cost-effective, precise, and easily controlled CNC solution that enables users — including small workshops, hobbyists, and designers — to efficiently carve and engrave on wood and plastic with minimal setup and high accuracy.

Objectives of the Work

- Design and build a CNC machine capable of carving and engraving on wood and plastic materials.
- Develop a three-axis system (X, Y, Z) with precise and stable mechanical movement.
- Integrate Arduino controller with GRBL Web interface for easy control and communication via serial port.
- Enable image-to-G-code conversion to simplify the process of generating carving instructions.
- Test and calibrate the machine to ensure high accuracy and reliable performance.
- Provide a user-friendly interface that allows adjusting carving dimensions, speed, and operational settings.
- Optimize the system for cost-effectiveness and accessibility for small workshops, hobbyists, and designers.

Scope of the Work

This project focuses on designing and implementing a CNC machine specialized in carving and engraving on wood and plastic materials. The scope includes the mechanical design of the three-axis structure (X, Y, Z), integration of the Arduino controller with the GRBL Web interface via serial communication, and the development of a user-friendly interface to adjust carving dimensions, speed, and other settings. The project also covers image-to-G-code conversion, calibration of the machine for precision, and testing the system to ensure smooth communication between hardware and software. The work does not include large-scale industrial manufacturing or integration with heavy-duty CNC systems but aims to provide a cost-effective, precise, and accessible solution suitable for small workshops, hobbyists, and custom production.

Significance of our work

This project delivers valuable contributions to both woodworking and plastic fabrication fields by providing a practical, efficient, and precise CNC system. It enables the creation of complex, artistic, and customized designs on wood and plastic with high accuracy and minimal effort.

Furthermore, the project empowers small workshops, artisans, and hobbyists to adopt CNC technology that was once limited to large industries, making advanced manufacturing more accessible. By reducing manual labor, improving productivity, and minimizing material waste, this system promotes cost-effectiveness, sustainability, and innovation in small-scale production and creative industries.

Organization of the Report

The sections of this report are organized as follows:

1. **Introduction:** Covers the problem statement, objectives, scope, and significance of the project in detail.
2. **Literature Review:** Reviews existing CNC technologies and methods, highlighting gaps and limitations that this project addresses.
3. **Methodology:** Describes the design, development process, and implementation strategy of the CNC system for wood and plastic materials.
4. **Results and Findings:** Presents the outcomes of the project, discusses challenges faced, and explains the solutions applied.

5. **Discussion:** Analyzes the broader implications, importance, and potential applications of the project's results.
6. **Conclusion and Recommendations:** Summarizes key achievements and provides suggestions for future improvements and enhancements.
7. **Appendices:** Includes technical diagrams, schematics, supplementary materials, and additional resources related to the project.

Constraints, Codes, and Earlier Coursework

Constraints and Limitations

Based on market research, most CNC systems available today are designed for industrial purposes and are often expensive. Few systems provide reliable performance at an affordable price, which limits accessibility for small-scale artisans and hobbyists. This project aims to bridge this gap by offering a solution that combines **quality, precision, and affordability**.

The following constraints and limitations were considered for the project:

1. **Material Handling:** The machine must be capable of handling various types of wood and plastic with different thicknesses and dimensions.
2. **Precision Carving:** Accurate engraving and cutting, especially for intricate designs, must be ensured through precise mechanical and software control.
3. **Cost Efficiency:** The system must remain affordable so that small workshops and individual artisans can use it.
4. **Ease of Use:** The control interface should be simple enough for users with minimal technical knowledge to operate efficiently.
5. **Mechanical Performance:** The machine must operate reliably under various working conditions and loads.

Codes and Standards

To ensure the CNC system's safety and proper functionality, several standards were followed throughout the project:

- **IEC 61010:** Applied for electrical safety in circuits and machine control.
- **NEMA 23:** Stepper motors were selected to meet this standard, ensuring precise movement control.

- Electrical components, including the **AC 230/240V, 170W spindle** and **220V power source**, were designed considering safety regulations.
- The **Arduino Mega 2560** was used as the main controller, managing operations via a hardware debounce circuit and controlling limit switches for homing procedures.
- **GRBL Library** was utilized for motion control, including M3/M5 spindle on/off commands, with software debouncing applied to reduce electromagnetic interference.
- An **RFID system** using Arduino Uno was implemented to authorize machine operation.
- **Emergency stop button** ensures immediate shutdown during unsafe conditions.

These measures guarantee compliance with safety standards and proper system performance within the defined operational parameters.

Earlier Coursework

Several prior learning experiences significantly contributed to the successful development of this project:

- **Microcontroller Programming (PIC and Arduino):** Gained through university materials and online resources, this knowledge was critical for developing the Arduino Mega-based CNC control system. It enabled us to program, debug, and manage communication between the controller and mechanical components.
- **Critical Thinking and Research Skills:** Helped us adopt a systematic approach to problem-solving, identify potential issues early, and implement effective solutions during the project.
- **Design of Digital Electronic Circuits:** University lectures and practical exercises provided essential knowledge for proper wiring, troubleshooting, and ensuring reliable electrical operation of the system.
- **JavaScript and Web Programming:** Learned through online tutorials and class exercises, this knowledge was applied to modify the GRBL Web interface and customize G-code generation to meet the project’s specific requirements.

These learning experiences collectively enabled the integration of hardware and software efficiently, ensuring the CNC system achieved the desired performance, accuracy, and usability.

Literature Review

CNC machines represent a significant advancement that has transformed multiple manufacturing and fabrication industries. They are essential tools in areas like woodworking, plastic fabrication, and artistic engraving because they allow for the **production of items with high accuracy and quality**. Compared to traditional methods, CNC machines enable the faster and more precise creation of complex designs.

CNC Wood and Plastic Engraving Machines

CNC engraving technology allows for precise sculpting and shaping of both **wood and plastic materials**. Using rotating cutting tools on a spindle, intricate designs and complex shapes can be achieved. These machines are widely used by small workshops and artisans to produce decorative items, furniture, and custom plastic components. The consistency of CNC engraving ensures high-quality results even for detailed patterns ([1]).

Stepper Motors and Motion Control

Stepper motors, such as **NEMA 23**, are employed to control the precise movement of CNC machines. These motors provide accurate positioning and repeatability, which is crucial for detailed carving on both wood and plastic. Drivers like the **TB6600** ensure smooth motion under varying loads ([2]).

Spindle Technology

The spindle, for instance, the **wolf mini grinder (230/240V, 170W)**, is a key component of CNC machines. It drives the cutting tool at high speeds, allowing for efficient and accurate carving. Lightweight spindles reduce the load on the Z-axis, improving precision and stability for both wood and plastic materials ([3]).

Limit Switches and Safety Mechanisms

Limit switches enhance machine safety by ensuring proper homing operations and restricting axis movement within safe ranges. They improve precision while protecting the machine from potential mechanical damage ([4]).

GRBL and Arduino Control

CNC machines can be operated using **GRBL firmware on an Arduino Mega 2560**, which interprets G-code commands and controls the motors and spindle. When combined with user interfaces like GRBL Web or UGS, this system provides an **accessible and user-friendly environment** for controlling CNC operations ([5]).

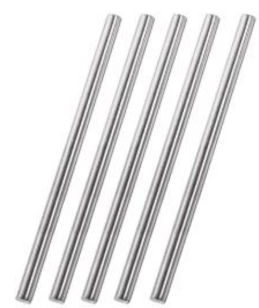
Methodology

Hardware Components

Material for Build Structure to move axis

- Stainless steel round rods with 8mm diameter were used for each axis.
- Iron lead screws were used to move each axis back and forth.
- Couplers were installed between the stepper motor shafts and the lead screws to ensure a secure fit and smooth motion.



Arduino Mega

The Arduino Mega 2560 is a microcontroller board built around the ATmega2560. It features 54 digital input/output pins, 14 of which can serve as PWM outputs, and 16 analog inputs. The board includes 256 KB of Flash memory, 4 UARTs for hardware serial communication, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The Mega 2560 R3 version introduces additional features, including SDA and SCL pins near the AREF pin, and two new pins close to the RESET pin: IOREF, which allows shields to adapt to the board's voltage requirements, and an unconnected pin reserved for future use. The Mega 2560 R3 is fully compatible with existing shields while remaining adaptable for new shields designed to utilize these supplementary pins.

Stepper Motor NEMA 23

Figure 6 Nema23

TB6600 Stepper Motor Driver

- The **TB6600 Stepper Motor Driver** is employed to control **NEMA 23 stepper motors** in the CNC system. It is capable of handling up to **4.5A per phase**, making it suitable for high-torque motor applications. The driver supports **microstepping up to 1/32**, allowing precise movement control while minimizing vibrations, which ensures **smooth and accurate motion** during cutting and engraving on both wood and plastic materials. This precision is essential for maintaining accuracy in the movement of CNC axes.

- A total of **three drivers** are required to control the **X, Y, and Z axes** of the machine.

Limit Switch digital electronics

Limit switches, rated at **5A**, are essential components in CNC systems, defining the **exact motion limits for each axis**. They ensure the machine operates within its predetermined boundaries by sending **digital feedback to the controller** when an axis reaches its maximum or minimum position. During homing operations, these switches allow the CNC system to establish a **known starting point**, preventing the machine from moving beyond its travel range and avoiding potential damage. For safe and precise operation of the CNC machine, **5A limit switches** are critical to maintaining both accuracy and reliability.

Figure 8 Limit Switch

Debouncing a switch with an SN74HC14 Schmitt Trigger

The components used in this debouncing circuit include **jumper wires, breadboard, SN74HC14N Schmitt Trigger, 1K and 10K Ohm resistors,** and a **0.1 µF ceramic**

capacitor. The **SN74HC14 Schmitt Trigger** ensures reliable and noise-free detection of limit switch signals in the CNC system. By eliminating signal fluctuations caused by mechanical bouncing, the Schmitt trigger provides the controller with a **stable digital signal**. The **capacitor (0.1 µF)** and **resistors (1K and 10K Ohm)** play a crucial role in filtering and stabilizing the signal. This configuration enhances the **accuracy and reliability** of homing and limit detection, ensuring smooth CNC operations free from unintended interruptions. Additionally, this circuit effectively mitigates **electromagnetic interference** generated by the spindle, which could otherwise affect limit switch signals even when software debouncing is applied.

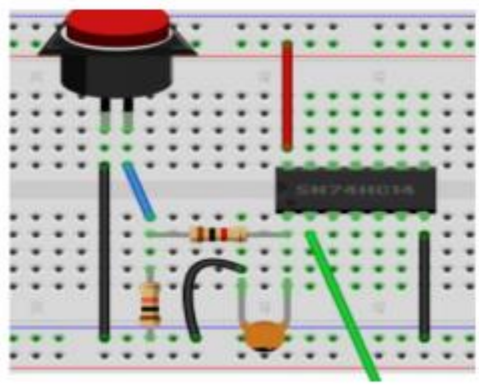


Figure 9 Debouncing a switch with an SN74HC14Schmitt Trigger

Relays

Since the Arduino operates at **5V**, it cannot directly control **high-voltage devices** such as the spindle and the jumper. To overcome this limitation, **5V relays** are used to act as switches for high-voltage circuits, allowing the Arduino to control them safely. In this project, **two relays** were utilized: one dedicated to controlling the **spindle**, and another to manage the **on/off operation of the jumper**. This setup ensures safe isolation between the low-voltage Arduino control signals and the high-voltage components of the CNC system.

Figure 10 10 5-volt Relay

Spindle

The **wolf mini grinder (230/240V, 50–60Hz, 170W)** is integrated into the CNC system and mounted externally, with a flexible shaft transferring motion to the spindle on the **Z-axis**. This configuration significantly reduces the **mechanical load on the Z-axis**, enhancing precision and minimizing wear on the stepper motor. Powered by the wolf mini grinder, the spindle is suitable for **light to medium-duty operations**, including engraving, cutting, and carving on materials such as **wood and plastic**, with adjustable speeds to accommodate various bit types. This setup ensures **efficient power transmission, stable performance, and improved accuracy**, making it ideal for precise CNC carving and engraving tasks.

Figure 11 wolf mini grinder

Emergency Stop Switch

The **Emergency Stop Switch** is a critical safety component designed to **immediately shut down the entire CNC machine** in case of malfunction or emergency. It works by **disconnecting the main power supply**, ensuring that all operations stop instantly to prevent potential damage to the system or harm to the operator. This feature provides a quick and reliable way to secure the machine during unexpected situations.

Arduino Uno

The **Arduino Uno**, based on the **ATmega328P** microcontroller, is a versatile and widely used platform for control and automation tasks. It features **14 digital input/output pins**, a **USB interface**, a **power jack**, and a **reset button**. In this CNC project, the Arduino Uno is utilized to **manage the main power supply**, enabling controlled **power on/off operations**, and is connected to essential components such as the **Emergency Stop**

Switch, the **On/Off switch**, and the **RFID modules**. This integration enhances the system's safety and ensures smooth operational control.

Figure 13 Arduino Uno

RC522 RFID Module

The **RC522** is a **13.56 MHz RFID module** powered by the **MFRC522 controller** from NXP Semiconductors. It is supplied with both an RFID **card and key fob** by default and supports multiple communication protocols, including **I2C, SPI, and UART**. In this CNC project, the RC522 is utilized as a **security and access control component**—requiring an authorized RFID card to **power on and operate the machine**. This ensures that only authorized users can access and control the system, enhancing its safety and preventing unauthorized usage.

Figure 14 RC522 RFID Module

Power Supply

A **computer power supply unit (PSU)** was selected for this CNC project due to its ability to deliver **stable and reliable power outputs** suitable for different components. It provides **5V** required for the **limit switches and control electronics**, and **12V** for the **stepper motor drivers**, ensuring consistent performance across all systems. Additionally, the PSU offers **sufficient current capacity** to meet the overall power demands of the project, contributing to safe and efficient operation.

Figure 15 Power Supply

Vacuum Cleaner

A **vacuum cleaner** was integrated into the CNC system to **collect wood and plastic debris generated during cutting and engraving operations**. Its suction head was mounted adjacent to the **spindle head**, ensuring efficient removal of splinters and dust directly at the source. The vacuum operates **independently from the main CNC system**, providing a cleaner workspace, improving visibility during operation, and helping maintain the longevity and precision of the machine.

Figure 16 vacuum cleaner

Hardware Implementation

Testing of Axes

After completing the **body assembly** of the CNC machine, we conducted comprehensive testing of each axis to evaluate **movement accuracy and precision**. Each axis (**X, Y, and Z**) was individually tested to ensure smooth travel and proper response to control inputs. Alignment and **calibration checks** were performed to verify that the machine's movements matched the expected commands accurately. These tests established a **solid**

foundation for the subsequent project phases, ensuring the machine could operate with **high precision, reliability, and consistency** in executing programmed instructions.

G-Code Drawing Test

Before installing the spindle, we tested the machine's drawing capabilities by attaching a pen to the Z-axis and running a G-code file. This step verified that all axes were moving correctly and that the machine responded accurately to the G-code commands. The test results confirmed proper functionality and precise execution of the programmed instructions.

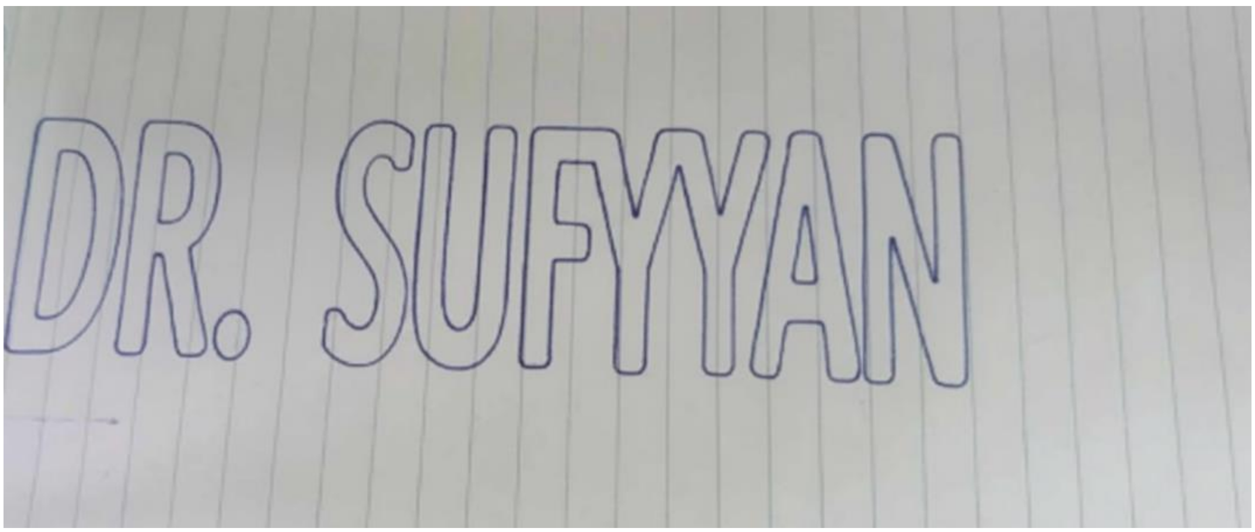


Figure 17 Test Draw

Limit Switch Installation and Testing

After completing the mechanical assembly, the **limit switches** were installed to ensure the machine operates within its designated travel boundaries. These switches play a crucial role in **preventing overtravel** and enabling the **homing feature**, which allows the CNC system to establish a precise starting point. Each limit switch was thoroughly tested to verify that it provides **accurate and reliable signals** to the controller, ensuring safe and precise operation during the machine's movement.

Spindle Installation and Electromagnetic Interference Handling

After installing the spindle and testing its operation, **electromagnetic interference (EMI)** was managed to ensure stable limit switch signals. A hardware debounce circuit was implemented using an **SN74HC14 Schmitt Trigger**, which effectively reduced noise and stabilized the signals. Additionally, **software debounce techniques** were applied to further enhance signal reliability and ensure smooth spindle operation with accurate feedback from the limit switches.

Carving Test

A carving test was performed to verify the accuracy and performance of the machine. We carved a specific shape, as shown in the attached image, using G-code instructions. The results demonstrated high precision and good quality, confirming the machine's readiness for its intended tasks.

Circuits diagram

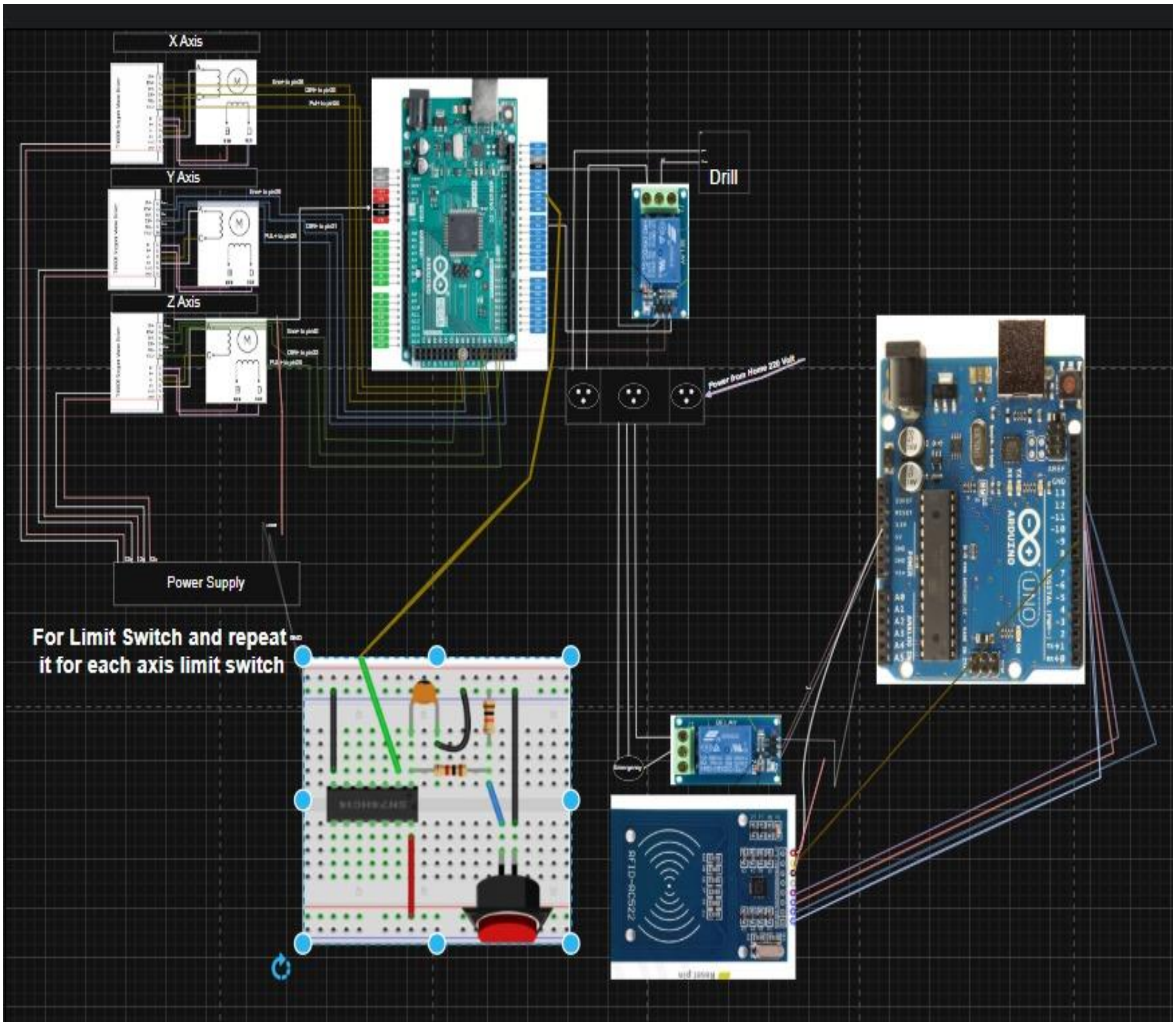


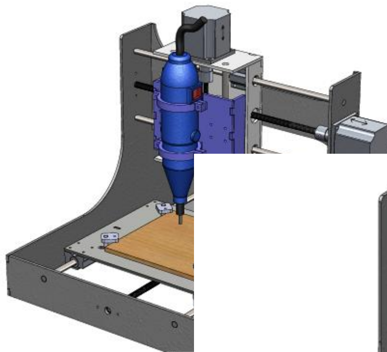
Figure 19 Circuit diagram

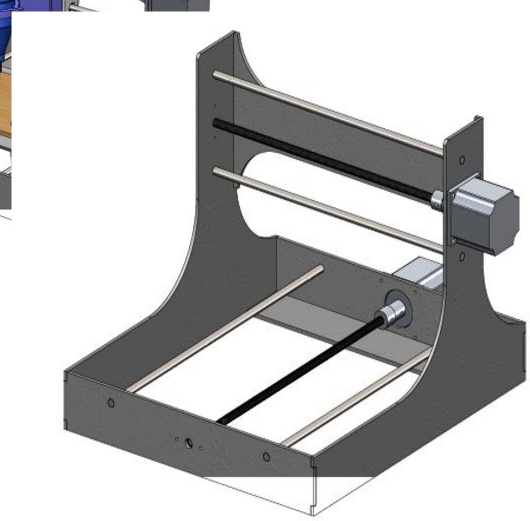
Software part

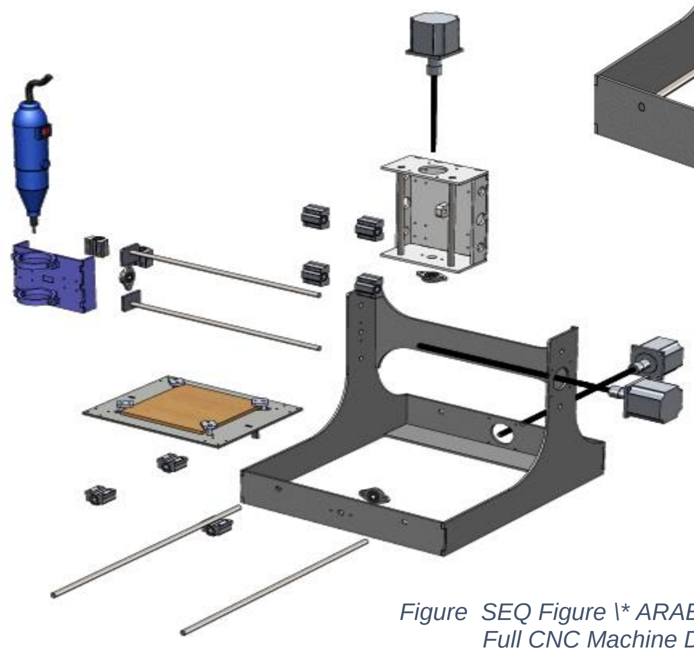
SOLIDWORKS Design

We used **SOLIDWORKS** to design the complete structure of the CNC machine, including the frame, stepper motors, and spindle. This allowed us to create a precise 3D model of the machine, visualize its assembly, and ensure the correct placement of each component before the manufacturing process. The design also helped in identifying potential mechanical interferences and improving the overall layout for stability and performance.

Figure 20 CNC Machine Full Assembly







nd Support Structure

*Figure SEQ Figure * ARABIC 21 Full CNC Machine Design*

G-code Simulation

At the beginning of the project, we learned the structure and commands of G-code. To better understand its operation, we developed a small simulation using Python to execute G-code commands and visualize the toolpath drawing.

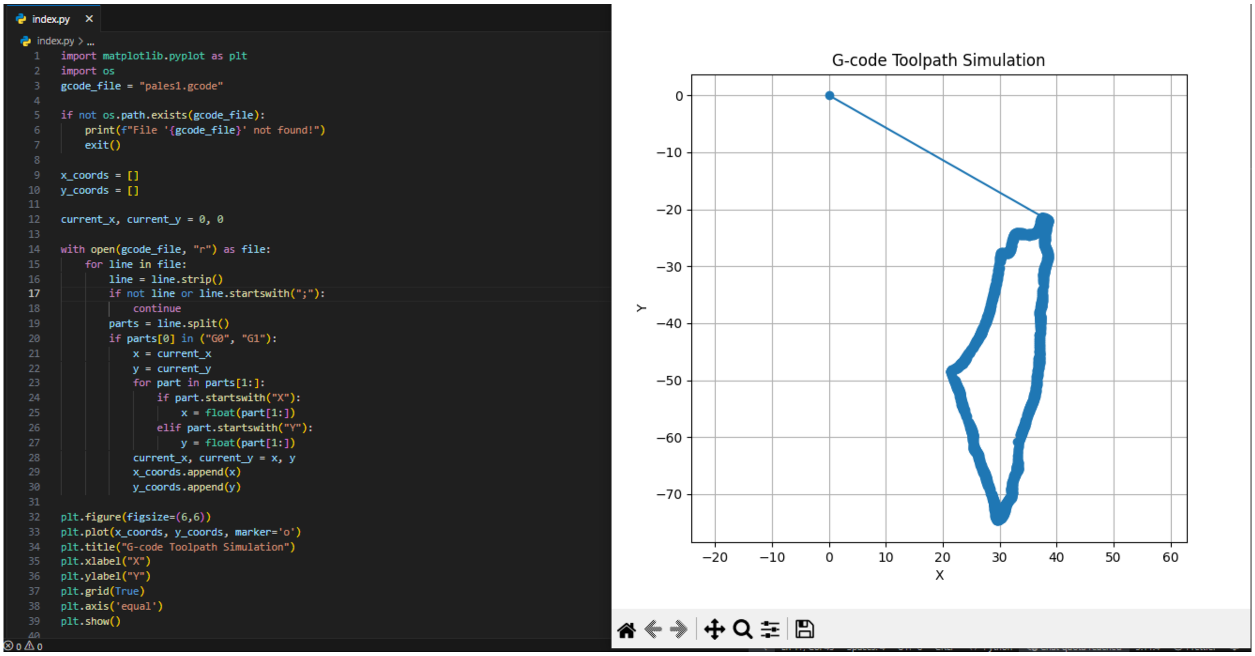


Figure 24 simulate G-code

GRBL Firmware Installation

The first step in the software phase was installing the GRBL firmware on the Arduino. After installation, we used the Universal G-code Sender (UGS) to transmit G-code commands to the GRBL controller for machine operation.

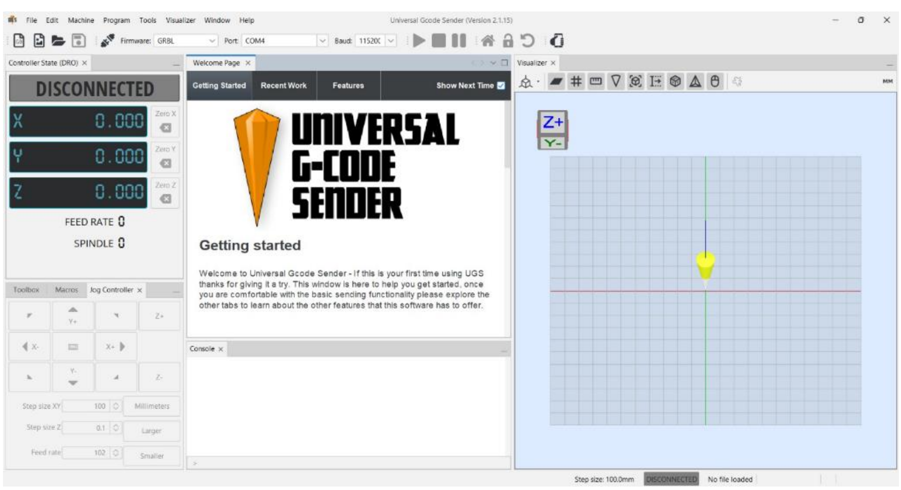


Figure 25 UGS

Applications Used

We utilized **Inkscape** to design letters, images, and other shapes, adjusting their sizes to match the wood pieces to be engraved. For converting these designs into G-code, we used **Web GRBL Master**, where we applied specific modifications to the code, including adding **M3** to start the spindle and **M5** to stop it after the engraving process.

The main software used for CNC control was **Universal G-code Sender (UGS)**. It provided multiple features, such as real-time simulation, remote machine control via phone, manual control, uploading G-code files to the CNC, and the homing function.

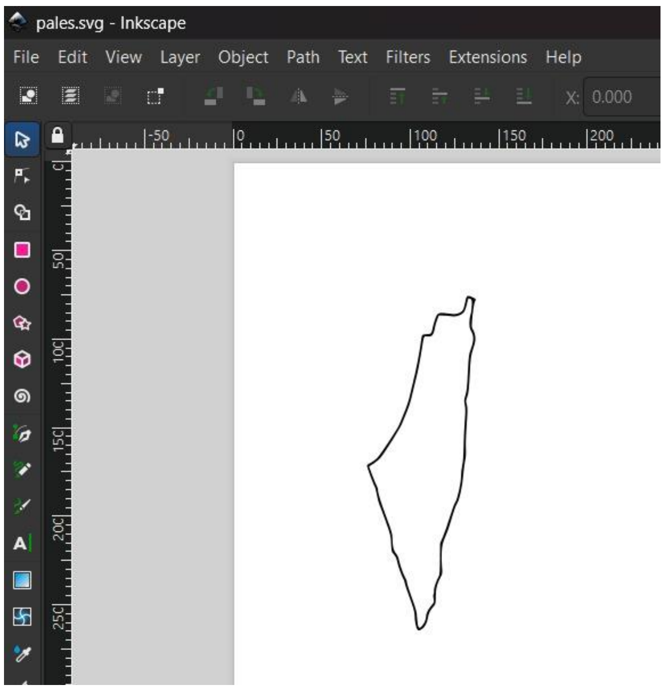


Figure 26 Inkscape Application

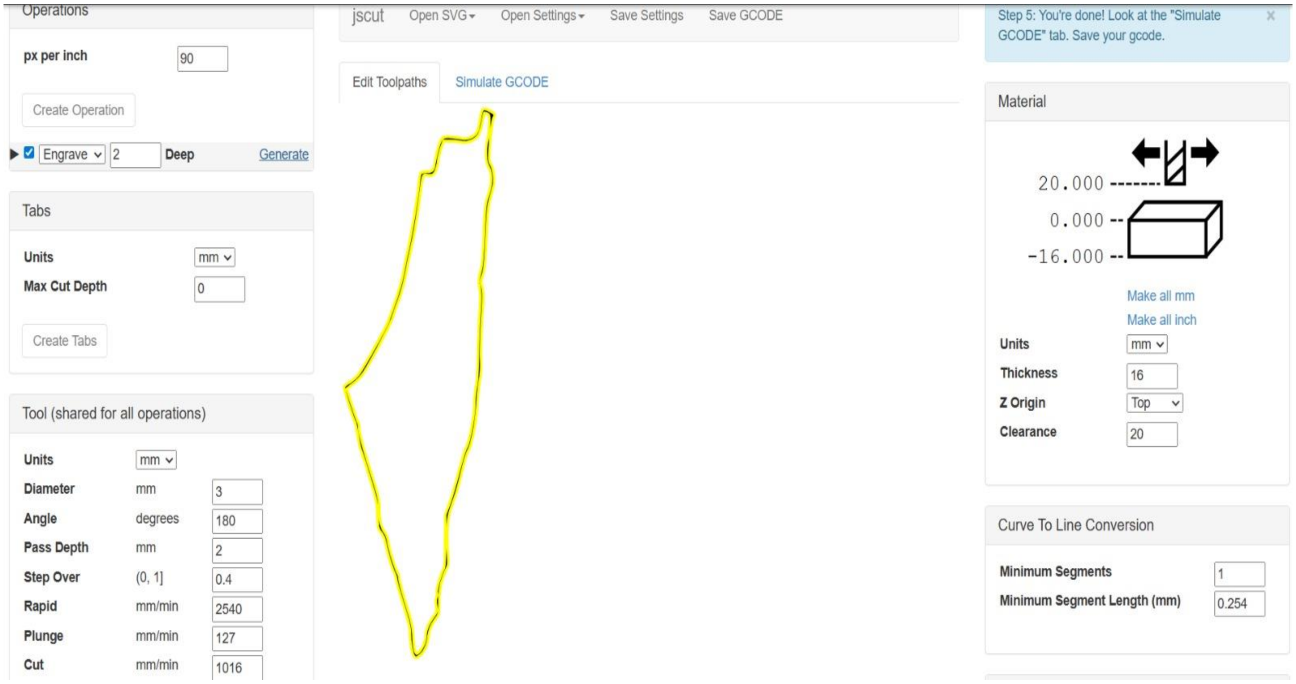


Figure 27 GRBL web master Setting

Arduino Uno Code

```
#include <SPI.h>
#include <MFRC522.h>

#define RST_PIN 9         // Reset pin for RFID
#define SS_PIN 10         // Slave Select pin for RFID
#define RELAY_PIN 3       // Pin connected to relay
#define INPUT_PIN 2       // Input pin to check HIGH state
MFRC522 rfid(SS_PIN, RST_PIN);
byte allowedCards[3][4] = {
  {0x12, 0xB6, 0xC4, 0x1D},  // Card 1 UID
  {0x06, 0xC7, 0x7B, 0xF7},  // Card 2 UID
  {0x01, 0x1A, 0x9A, 0x1F}   // Card 3 UID
};
void setup() {
  Serial.begin(9600);
  SPI.begin();
  rfid.PCD_Init();
  pinMode(RELAY_PIN, OUTPUT);
  pinMode(INPUT_PIN, INPUT_PULLUP);
  digitalWrite(RELAY_PIN, HIGH);
  Serial.println("System ready. Waiting for PIN 2 HIGH...");
}
void loop() {
  if (digitalRead(INPUT_PIN) == HIGH) {
    if (rfid.PICC_IsNewCardPresent() && rfid.PICC_ReadCardSerial()) {
      if (isAllowedCard()) {
        digitalWrite(RELAY_PIN, LOW);
        Serial.println("Relay ON: Card matched and PIN 2 is HIGH.");
      } else {
        Serial.println("Unauthorized card.");
        digitalWrite(RELAY_PIN, HIGH);
      }
      rfid.PICC_HaltA();
    }
  } else {
    digitalWrite(RELAY_PIN, HIGH);
    Serial.println("LOW...");
  }

}

bool isAllowedCard() {
  for (int i = 0; i < 3; i++) {
    bool match = true;
    for (byte j = 0; j < rfid.uid.size; j++) {
      if (rfid.uid.uidByte[j] != allowedCards[i][j]) {
        match = false;
        break;
      }
    }
    if (match) {
      return true;
    }
  }
  return false;
```

Figure 28 Code RFID

Arduino Uno Code Explanation

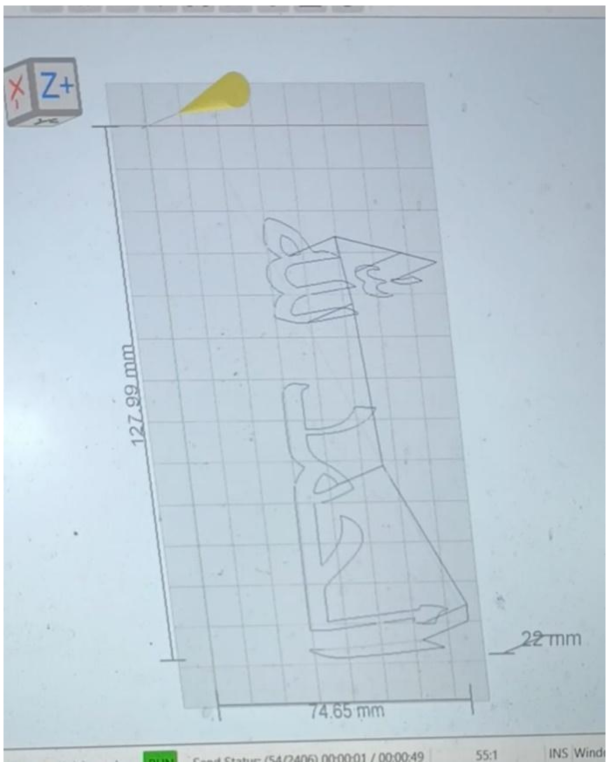
This Arduino Uno code manages the operation of a device by integrating an **RFID card reader** with an **additional security condition**. The system reads the **UID (Unique Identifier)** of an RFID card and checks it against a predefined list of authorized cards stored in the program.

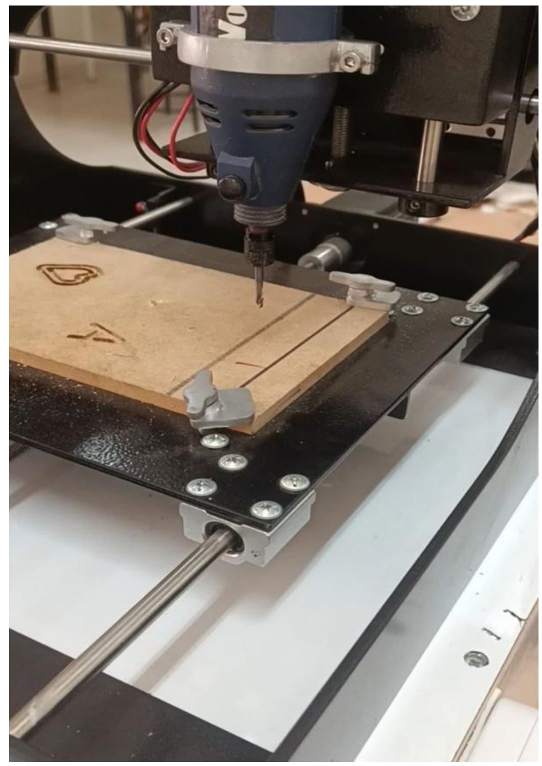
In addition to verifying the card, the system monitors **PIN 2** for a **HIGH signal**. Only when **both conditions are satisfied**—an authorized card is presented **and** the input pin is HIGH—does the system activate the **relay**, turning the device **ON**.

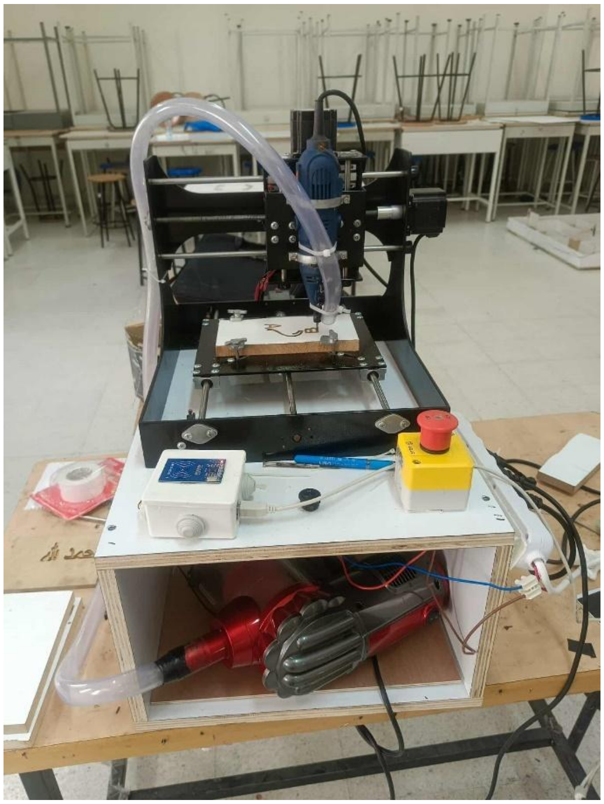
If either condition fails, the relay remains **OFF**, ensuring the device stays inactive. This setup enhances **security and controlled access**, making it suitable for applications such as **access control systems** or **secure equipment activation**.

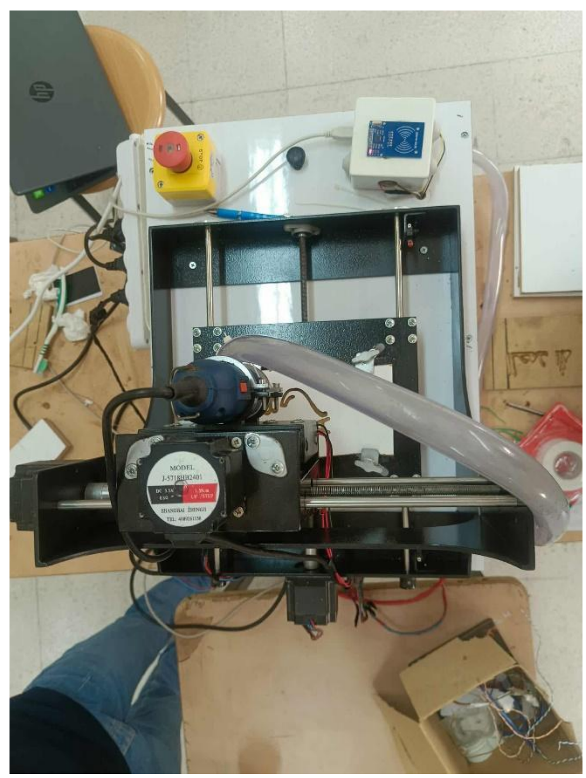
Result

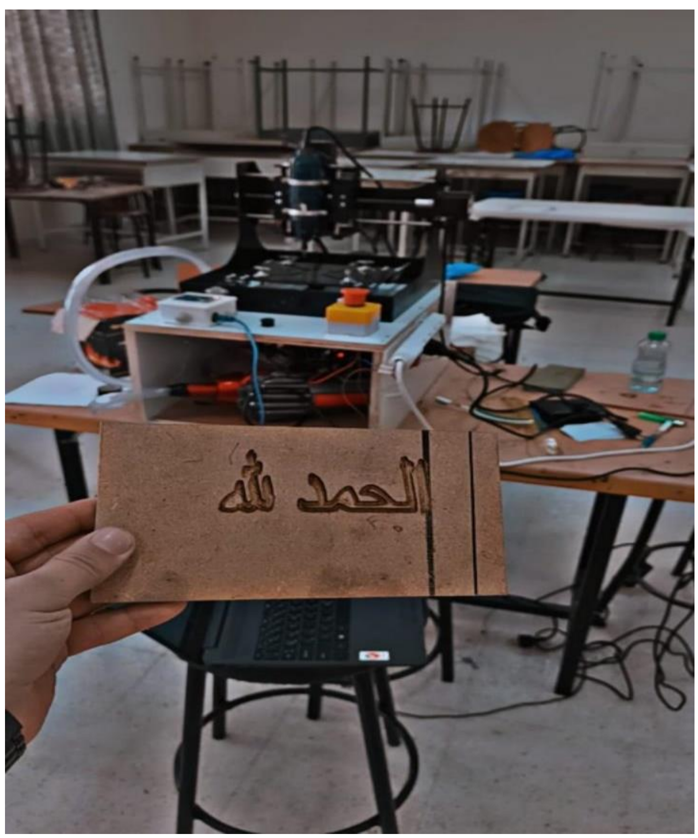
At the end of the project, we were able to build a CNC machine capable of sculpting the required shapes accurately. It can be controlled through G-code or via the UGS program's controller section, either directly from the computer or remotely from a smartphone.







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Discussion

The CNC Sculpture project demonstrates the successful integration of **mechanical, electronic, and software systems** to achieve precise and efficient carving and engraving, fulfilling the intended design objectives. The project emphasizes the importance of balancing **performance, cost-effectiveness, and reliability** to develop a functional CNC machine suitable for a variety of applications.

Key design considerations included ensuring **smooth movement across all axes**, maintaining **high precision**, and enhancing the **overall stability and productivity** of the system. Electromagnetic interference between the spindle and limit switches was effectively managed using a **hardware debouncing circuit**, ensuring accurate and reliable signal detection.

The careful selection of components—such as the Arduino Mega 2560, NEMA 23 stepper motors, and wolf mini grinder spindle—reflects a tailored approach to meet the machine's performance requirements. The spindle motor was directly mounted on the Z-axis, ensuring compact design and straightforward power transmission, while maintaining reliable precision and functionality.

Overall, the machine demonstrates **high efficiency, consistent output, and versatility**, with the potential for further performance improvements by increasing spindle power or adapting the spindle head for different tasks. This design ensures reliable and productive operation across a range of materials.

Conclusion

The CNC Sculpture project successfully demonstrates the design and construction of a **reliable machine capable of precise cutting and engraving on various materials, including wood and plastic**. The system effectively integrates advanced concepts with carefully selected hardware components to **enhance accuracy, reduce mechanical strain, and optimize overall performance**.

Its **versatile and straightforward design** highlights its practical value for multiple carving and engraving tasks while leaving room for future enhancements. Overall, this project illustrates the **application of technical and engineering knowledge** to address real-world CNC challenges, achieving the intended goals with **efficiency, precision, and consistent output**.

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