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Development and Evaluation of a Low-Cost CNC Wood Carving Machine for Artisanal Applications

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***Abstract*—Improving the quality of the produced artwork would require the development of computer numerical control (CNC) technology for various wood shaping processes. This paper presents the development and implementation of a CNC wood carving machine. This project aims to produce wood carvings with high precision and low cost. The electronic components were selected, the mechanical frame of the machine was built, and all parts of the machine were assembled and installed. The presented wood carving machine is based on the principle of drawing the desired shape, translating it into G-code, and then sending it to the microcontroller program. The microcontroller sends instructions to the CNC shield, which drives three stepper motors in a synchronized manner in order to produce the desired carving model. The maximum workpiece of the caving machine designed to be 30x30 cm. Experiments were conducted to test the functionality of the proposed CNC wood carving machine. The results showed that the carved models created by this machine had a carving precision range from ±0.1 to ±0.15 mm and a carving speed of approximately 500 rpm. The proposed CNC can be used to produce low-cost artisanal woodwork applications.**

Keywords—Carving; 3D CNC; Arduino Microcontroller; Stepper Motor; G-Code; DRV8825 Driver.

I. INTRODUCTION

In the modern day, technology is utilized in a wide variety of aspects of everyday life [1]-[3]. As we become more reliant on the utilization of technology on a daily basis, whether it be for communication, transportation, the quest for information, or even entertainment and sensitive issues such as health in several medical fields [4]-[7], we are becoming increasingly dependent on utilizing technology including safety and rescue operations [8], [9]. In recent decades, there has been a growing trend toward the utilization of robots in order to attain more comfort in the task that requires physical effort to complete, such as wood carving, as well as other laborious activities, such as construction work [10]-[15]. The application of such technology in the field of wood carving results in increased productivity, decreased costs associated with labor, and improved accuracy in the task completion [16]. The utilization of robots in industrial applications is becoming more prevalent in the carpentry sector [17]. Industrial robots are a significant investment that provides the flexibility to complete tasks in the carpentry industry [18]. The collaboration between humans and robotics in woodworking applications has been improved as technology advances, a critical component of carpentry that facilitates the implementation of the engravings and linear symbols that carpenters create on wood [19]. A study proposed a Computer Numerical Control (CNC) wood engraving machine is engineered using a 3-axis stepper motor to get high precision [18]. The CNC wood engraving router in Bali is engineered to enhance productivity and efficiency, ensuring precise and uniform wood engraving outcomes. The G-code software utilized in CAM processing employs MACH 3 software.

The utilization of CNC technology has proliferated across numerous domains and applications [20]-[22], including wood painting [23], plotter devices [24], [25], printed circuit boards (PCBs) [26], [27], wood milling [28], [29], and cake decorating [30], [31]. A CNC is a machine that is controlled by a computer using a particular control software that generates a necessary shape with exceptional workmanship and high precision that is impractical for humans to do manually. 3D printers are an important class of CNC systems and are not used for milling and cutting but for printing and building small components from various materials with high hardness that can be used to create durable industrial machines [32], [33].

In addition to printing complex parts of various sizes and shapes that are difficult to create with a lathe. For these reasons, 3D printers and their products are becoming increasingly popular and important [34], [35]. These printers are being used in many fields, including the food industry [36]. A commercial syringe/extruder printer was developed for the investigation of 3D printing of white chocolate based on extrusion [37].

CNC machines were used in the development of carpentry work in the mid-twentieth century, and most professions and industries were automated using computers [38]. CNC technology has expanded the functionality of carpentry tools and machines, allowing them to manufacture more intricate wood carvings faster and at an affordable price [39]. The use of CNC wood carving technology has greatly increased efficiency and precision in the production and carving of unique furniture designs [40]. As a result, furniture elements

like doors, beds, and table legs have elaborate designs. This practical technology helps manufacturers meet client needs through improved manufacturing processes, reduced material waste, high repeatability, and customization and distinction [41], [42]. The CNC machines have become affordable due to technological advancements in recent decades. As a result, a low-cost CNC machine for wood curving has been developed. The reference study utilizes an Arduino ONE and stepper motors. This machine is effective on a wide range of wood materials, making it a good choice for woodworking applications [43].

The combination of machines and computers in CNC is essential for producing precision tools at low costs without compromising on quality. These machines can be adapted for a variety of uses, such as engraving, carving, and creating commercial branding on a variety of materials. This adaptability has boosted the use of CNC machines and made the technology affordable and accessible to small workshops and businesses. CNC machine prices have dropped due to developments in microcontrollers, resulting in the formation of CNC marketplaces for domestic and hobbyist use. Manufacturing continues to rely heavily on CNC machines, which require continuous improvement [44]-[46].

CNC machines make it possible to design and generate complex patterns and decorations that boost the visual value of a building space, as architectural carpentry are a key component of decorating any building or space. The CNC machines have become an important tool for creative works in the field of art and wood carving. The possibilities offered by CNC carving machines have increasingly pushed the bounds of traditional woodworking processes, as the artist has created beautiful artworks, incentives, and ornaments with shapes full of small and precise features. The artist can now professionally develop novel shapes, surfaces, and proportions according to this technology. CNC machines convert digital images of the design into a three-dimension (3D) object that shows fine details. Using these machines is the most efficient method to cut and carve wood and metal. The appropriate materials for carving with the proposed CNC system are cork, cardboard, wood, and similar substances.

The development of CNC wood cutting, carving and shaping techniques has improved the quality of the artwork produced. With these techniques, it is possible to obtain high-precision, low-cost products and perform more complex and repetitive manufacturing operations. The digital drawing utilizing touchscreens technologies in graphic applications has also enhanced the use of CNC in wood carving and drawing. As a result, the quality of wood sculptures is enhanced and the process is simplified.

The practical applications of CNC machines in woodworking branch out into a wide range of sectors, which all share that they require precision and are controlled by computers to achieve quality results. The proposed CNC machine relies on the results of previous research that has established the technological foundations for this subject. These foundations illustrate the way that CNC technology can be applied to woodworking and wood carving through modern design and component selection that takes into account cost as well as practical and useable results. It applies knowledge to industrial applications and establishes the standard for what is possible with numerically controlled woodworking and carving.

II. HARDWARE COMPONENTS

A description of the key components of the proposed system and their features is presented as follows. These components were chosen due to their affordability, widespread commercial availability, and adequacy for effective task performance.

A. Arduino Uno

It is a programmable microcontroller that can interact with sensors, LCDs, relays, motors, and many other electronics circuits. It can be used to control robots, smart systems, IoT projects and many other applications [47]-[49]. Fig. 1 shows an Arduino Uno board that has many features including 6 analog inputs and outputs, 14 digital inputs and outputs, 2KB of RAM, 32KB of memory for storing programs, and a USB port for power. It is possible to program the Arduino microcontroller using C++.

Fig. 1. Arduino Uno microcontroller

The Arduino Uno is chosen because it is easy to program and use, as well it can be easily connected to a large number of applications and libraries, and has a processor that is sufficient to control a similar CNC system. Other microcontroller alternatives may not have the same level of ease of use, programming, and compatibility with CNC accessories.

B. CNC Shield

It is a board used to enable Arduino microcontrollers to drive different types of machines. It functions as an interface between the microcontroller and stepper motors, essentially facilitating the control of robots, 3D printers and CNC machines [25], [50]. It can drive four stepper motors for x, y and z axes and the fourth motor can be used for some auxiliary tasks of the system. It is shown in Fig. 2, with four DRV8825 stepper motor driver female connectors. For these features it was chosen because it makes controlling small CNC machines easier with simpler electrical connections, in addition to supporting software like grbl. Other CNC controller alternatives like Mach3 or LinuxCNC are usually more expensive and complex.

C. DRV8825 Stepper Motor Driver

The stepper motor driver, shown in Fig. 3, provides precise, reliable, and high-performance control of stepper

motors in many applications such as robots, CNC machines, and 3D printers [51], [52]. It comprises a micro-stepping indexer and two H-bridge drivers, and provides six micro-stepping resolutions from one step down to 1/32 step. It can drive each output to produce up to 2.5A of current. It was chosen for its ability to drive stepper motors with a higher current rating, allowing it to drive more NEMA-17 motors. Other alternatives such as the A4988 have lower current ratings, which may limit the number of stepper motors that can be driven.

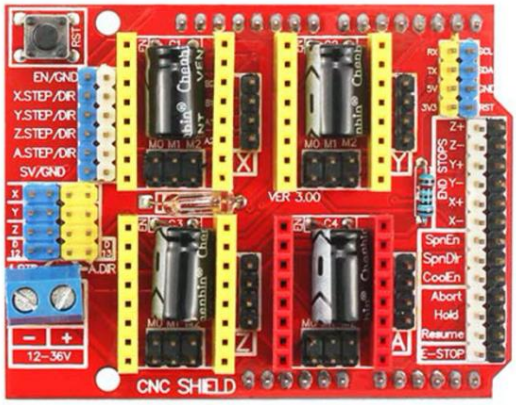

Fig. 2. CNC shield

Fig. 3. DRV8825 stepper motor driver

D. NEMA-17 Stepper Motor

The stepper motor is a brushless dc motor with high torque, low speed and high position control resolution [38], [53]. It has a resolution of 200 steps per revolution, which means it rotates by 1.8 degrees per step. The NEMA-17 stepper motor is shown as in Fig. 4. To control the rotation of the stepper motor, a series of electrical pulses are sent to the motor driver, each of these pulses results in a single step rotation. NEMA-17 Stepper motor is chosen for its precision, flexibility, reliability, and broad compatibility. Other alternatives, such as NEMA-23, have a higher torque but are larger, more expensive, and consume more power, making them unsuitable for small CNC machines. Smaller motors, such as NEMA-14, are also an alternative, but they can't provide the torque required for precise CNC operations.

E. Power Supply

The Buck XL4016 converter is used to supply power to the microcontroller and stepper motors in the CNC machine [54], [55]. The voltage and current requirements for the microcontroller, CNC shield and drivers are approximately 12V, 150mA, while each stepper motor requires 5V, 1A. In a buck converter, 220V is converted to 12VDC before being stepped down to 5VDC by the regulator circuit. It features a high efficiency of up to 95%, which reduces the amount of heat generated and helps prevent overheating. This results in longer battery life and less heat dissipation due to its dual heat sink design, ensuring the system stays cool and functional for extended periods. It is also designed to provide consistent performance and long-term reliability [56], [57].

Fig. 4. NEMA-17 stepper motor

III. CARVING MACHINE DESIGN AND IMPLEMENTATION

The CNC machine was designed using SketchUp. it is a fast tool for creating 3D models and basic designs with ease [58], [59]. Professional CAD tools outperform this software in terms of advanced parametric modeling, complex assemblies management, and geometric analysis validation. For the proposed CNC design, it does not require high levels of complex assemblies and geometric analysis validation. For simplicity, the choice to use SketchUp was appropriate and sufficient to create the required designs.

Bresenham's algorithm for linear interpolation with acceleration control was used for precise and synchronized control of three stepper motors. The Bresenham's algorithm is simple algorithm that used in many graphics libraries and is found in the grbl library [60]. The acceleration control tool of the Arduino AccelStepper library helps to regulate the acceleration of the stepper motors in order to prevent step skipping [61], [62].

The Bresenham's algorithm selects the stepper motor that will operate to maintain straight-line motion and ensures that the three motors remain synchronized. Then the acceleration control adjusts and optimizes the performance of the stepper motors using gradual acceleration and deceleration. The DRV8825 drivers then adjust the micro-stepping in 1/16 or 1/32 steps to increase the resolution. All of this is included into the grbl library with G-code commands.

In the x-axis, the CNC machine moves in the horizontal direction forward and backward in the workspace. The linear slide mechanism is designed to move on this axis by a stepper motor to obtain this movement and improve its repetitive motion. Fig. 5 shows the horizontal linear slide mechanism of a CNC machine in x-axis.

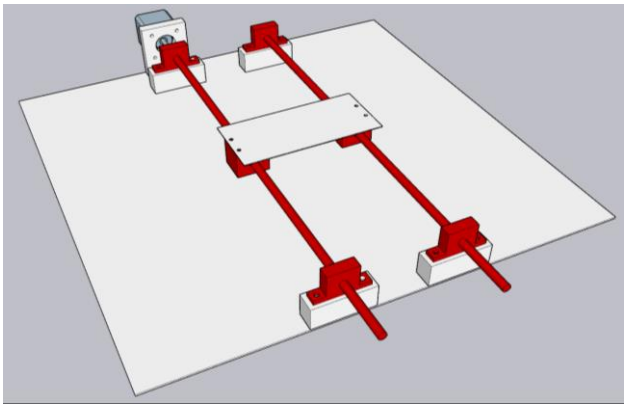

Fig. 5. Linear slide mechanism for the CNC machine in x-axis

In the y-axis, the CNC machine moves in the horizontal direction to the right and left in the workspace. The CNC is moved on a horizontal linear slide by another stepper motor on this axis. Fig. 6 shows the horizontal linear slide mechanism of a CNC machine in y-axis.

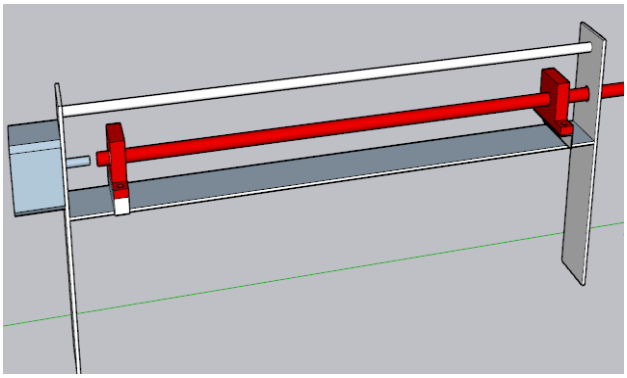

Fig. 6. Linear slide mechanism for the CNC machine in y-axis

The third axis is the z-axis, which is the axis perpendicular to the surface of the work-piece. The third stepper motor is used in the carving process precisely by moving the carving tool on this axis to show its effect on the depth and shape of the work-piece. There is a twin slider mechanism to secure the movement of the carving tool on this axis. One slide is operated to regulate the vertical movement, while the second slide functions as a stabilizer, ensuring rigidity and decreasing vibration during operation. Fig. 7 shows the double slide mechanism that moves in z-axis.

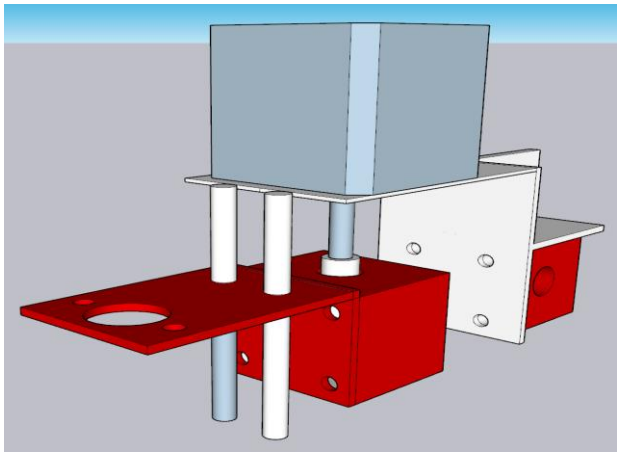

Fig. 7. Double-sliding mechanism operating in the z-axis

This method of managing the motion system ensures that the carving system tools are able to reach all points in the work-piece accurately and reliably.

The design of the proposed CNC machine is based on moving the work-piece forward and backward on the x-axis, while the head holding the carving tool can be moved left and right on the y-axis and up and down on the z-axis as shown in Fig. 8. The maximum workpiece size is designed to be 30 × 30 cm.

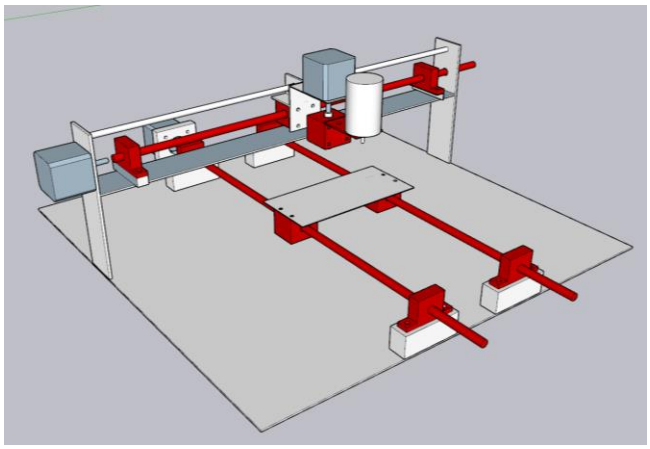

Fig. 8. The proposed CNC machine

Potential challenges such as wear, alignment errors and vibrations are considered in the design of the sliding mechanisms of the CNC wood carving machine. To reduce wear, cast iron bars are used and periodic lubrication is adopted to reduce friction. To reduce alignment errors, assembly points are checked and trial and error is used before installing the welding points. Moreover, periodic maintenance is adopted which results in long life and good performance stability.

Vibration is a threat to the accuracy of carving, so the proposed CNC machine is placed inside a strong wooden case with a rubber plate under the machine body as a vibration damper to ensure the stability of the machine. This reduces the vibrations that occur during wood carving and cutting.

The frame of the CNC wood carving machine is important because it acts as the backbone of the machine that provides stability and support to all other parts so it is made of solid steel for durability. The main frame of the proposed CNC machine is shown in Fig. 9.

The stepper motors are then installed on the frame as shown in Fig. 10. These motors are important for accurate movement of the CNC along the x, y and z axes.

Then the electronics and wiring are connected and installed. The CNC shield is incorporated into the system by matching the CNC shield connectors to the Arduino UNO. Next, attach the DRV8825 modules to the dedicated pins of the CNC shield as illustrated in Fig. 11. Next, link every stepper motor to the appropriate controller so that it can operate in the x, y, and z axes.

Fig. 12 shows the drivers aligned to Arduino microcontroller that connected to the power supply and other electronics.

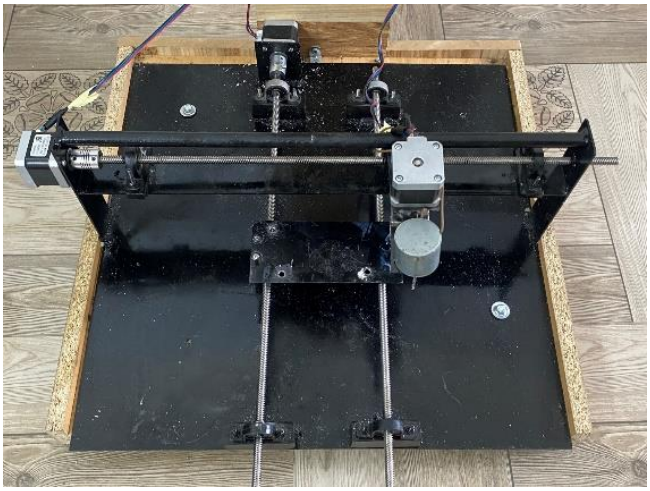

Fig. 9. The frame of the proposed CNC machine

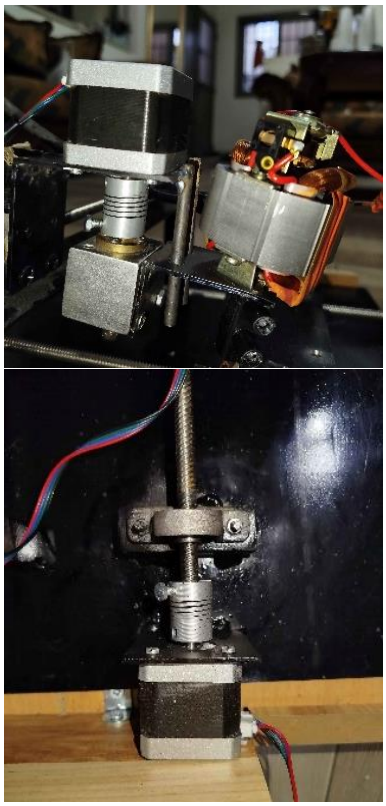

Fig. 10. Installing stepper motors on the frame

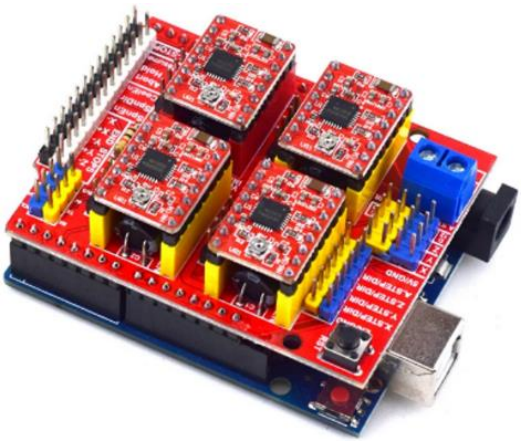

Fig. 11. CNC shield and DRV8825 modules integrated with Arduino UNO

Fig. 12. The electronics component and the power supply

The operational and control switches for the main stepper motor, which drives the cutting and carving tools, are integrated so that the system get an instant way to shut down in case of emergency. This assures safe operation and enables easy starting and stopping of the machine. Fig. 13 shows the final developed CNC wood carving machine after it has been assembled and execute wood carving work.

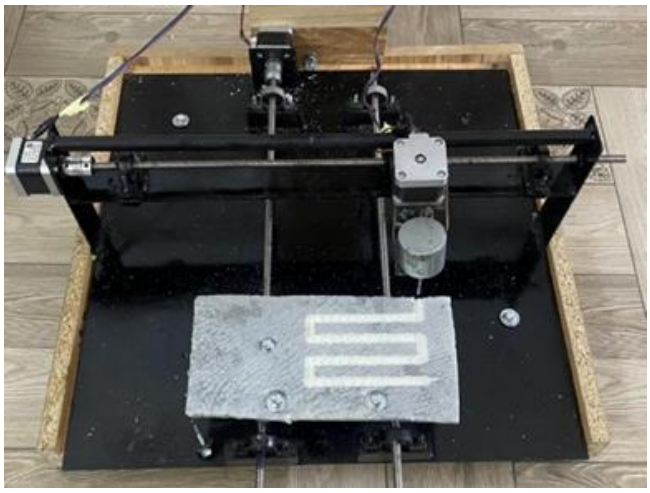

Fig. 13. Final CNC wood craving

IV. SOFTWARE IMPLEMENTATION

The Arduino microcontroller can be programmed in C++ as it has an integrated development environment that supports many libraries, and the grbl library has been used to program the Arduino. Grbl is an open-source software used to control the motion of a CNC machine. It can be easily downloaded to Arduino to get a high performance and affordable control system. It uses G-code as input while the output of the Arduino microcontroller is motion control commands.

G-code, or Geometric Code, is a programming language that is used to guide the movement of 3D printers and CNC machine tools. It provides instructions for different types of machine tools to use and the way to move in Cartesian coordinates, and is generated using Solidworks software. In addition, it supports plenty of other inputs including feed rate, rotating angles, speed, tool length offset, start and stop points, wait time, etc. Universal G-code Sender (UGS) is used to coordinate operations with the CNC shield on the Arduino. UGS is a software based on an open-source platform, used to send G-code instructions to the CNC machine.

The CNC machine is calibrated by determining the exact rotation of each axis in accordance with predetermined commands to ensure exact movement. The steps per millimeter are then calculated and updated in the grbl settings. Finally, the driver is adjusted to determine the proper current in order to avoid step loss or motor overheating. After the calibration is completed, prepare the G-code files and upload them to UGS. Then, place the machine tool at the required location and run the program to put the CNC machine into operation mode.

V. METHODOLOGY

Fig. 14 shows the functionality diagram of CNC wood carving machine, which explains the steps required to achieve any desired wood carving process using this machine. It starts by drawing the desired shape and converting it to G-code using a Solidworks software. The G-code is then sent to UGS which in turn feeds it into the grbl library. The grbl library is called by the C++ program used to program the Arduino microcontroller. The microcontroller executes the instructions of this library using the CNC shield and the DRV8825 driver. The driver is connected to the stepper motors of the CNC machine that carves wood using CNC to achieve the desired final outcome.

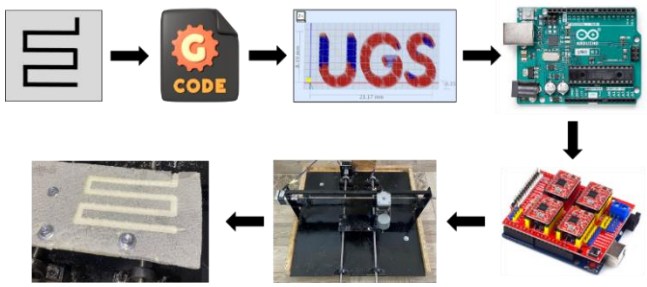

Fig. 14. The functionality diagram of CNC wood carving machine

The CNC wood carving machine flowchart in Fig. 15 shows that the Arduino reads the G-code generated from the drawn shape and sends commands to the CNC shield to implement these instructions. The CNC shield distributes the commands to the DRV8825 drivers. The DRV8825 drivers control three synchronized stepper motors to carve the wood until the desired position is achieved. When reaching the desired position, the Arduino will check whether there are more wood carving tasks and complete the carving or end the tasks.

The CNC system performs a number of operations including milling, cutting, engraving and drilling and accomplishes them with reasonable efficiency and precision. The proposed CNC system uses a NEMA-17 stepper motor with a resolution of 200 steps per rotation, where one step equals 1.8°.

The DRV8825 driver features micro-stepping technology that enables precise control of stepper motor at one step, half step, quarter step, and even 1/32 step. This implies that the stepper motor's position can be precisely controlled, allowing for rotational control with an accuracy of up to 0.05625° (i.e. 1.8°×1/32 step =0.05625°). The CNC machine made it possible to execute wood carving designs at a satisfactory level.

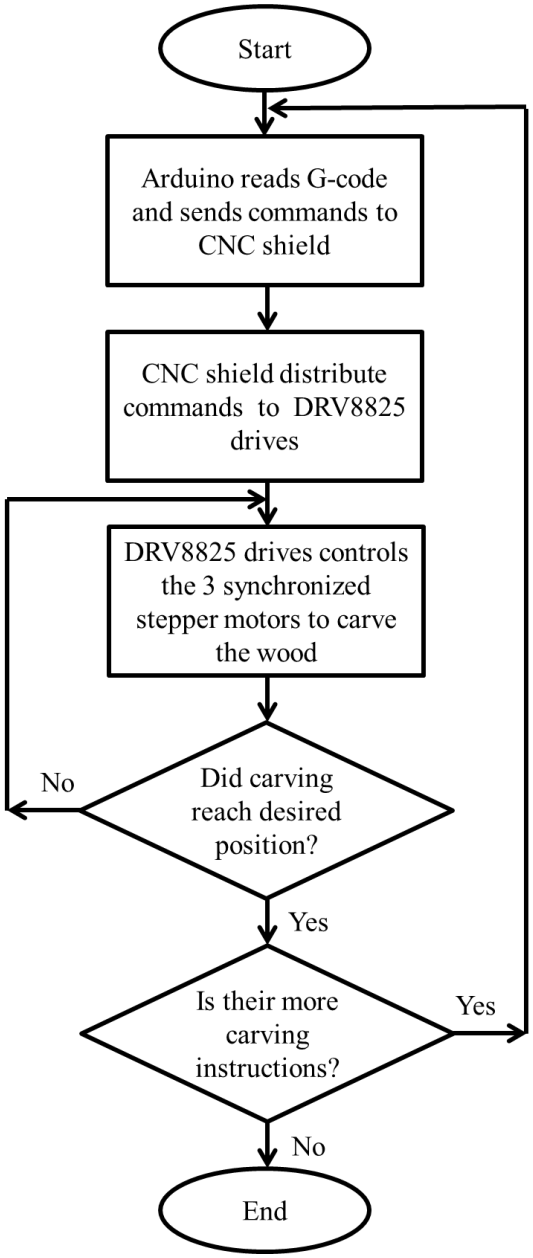

Fig. 15. The flowchart of CNC wood carving machine

VI. RESULTS AND DISCUSSIONS

The proposed CNC machine can carve on cork, compressed cardboard and wood of different types such as maple, redwood, yew and spruce. The prototype was tested to verify the machine's ability to convert various digital drawings into carving models. The results obtained by repeating the carving process several times showed that the precision ranged from ±0.1 to ±0.15 mm. This was achieved by setting the DRV8825 drivers to a micro-stepping of 1/16 or 1/32 steps and the stepper motors to rotate at a speed not exceeding 500 rpm. The results showed satisfactory performance of the machine, as shown in Fig. 16, where the proposed CNC machine shows the consistency and cutting accuracy as well as the machine's reliability and execution efficiency.

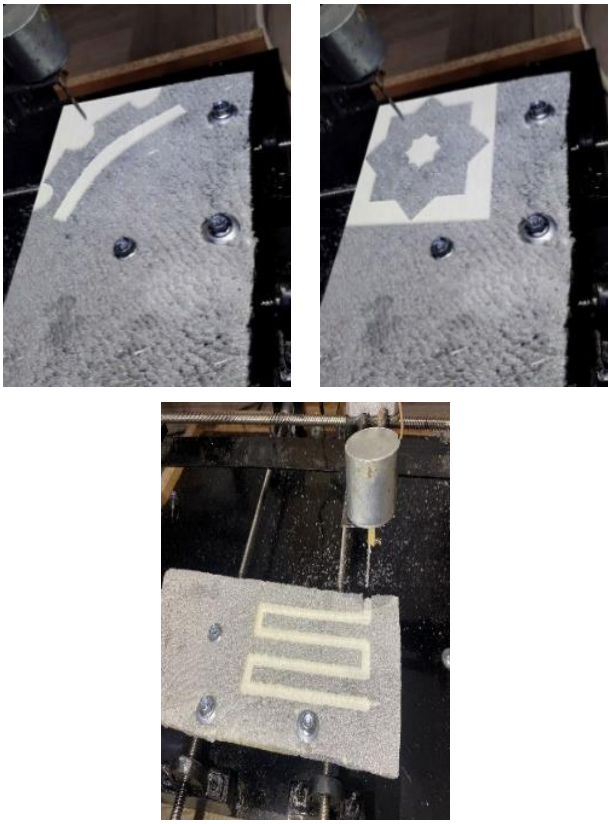

Fig. 16. The output of the wood carving CNC machine

The use of Arduino microcontrollers makes it possible to easily control and monitor carving devices, which are becoming increasingly accessible as technology advances. The design of the CNC wood carving machine that was presented had the aim of lowering expenses, improving the precision of the carving process, and reducing the amount of time that was required to complete the required carving in comparison to the conventional methods. As a result, the design that was developed is presented in order to accomplish both stability and safety. In addition, automated carving offers advantages in terms of a high level of repeatability, which allows for the reproduction of exact carving models. There is a possibility that this prototype may open the way for the future incorporation of carving arts into the furniture industry.

A comparison between the proposed CNC machine with some similar studies reported in [63], [64] is presented in Table I which highlighting the main feature of the proposed design.

The CNC shield is more cost-effective and user-friendly, as well as easier to program, compared to alternative controllers such as Mach3 [65] or LinuxCNC [66], which are more expensive and complex. The DRV8825 stepper motor driver is equipped with a high current rating, which enables it to operate more stepper motors. In contrast to other alternatives, such as the A4988, which have lower current ratings that restrict the number of stepper motors that can be driven. The NEMA-17 Stepper motor is selected over available alternatives, such as the NEMA-23, which are more expensive, utilize more power, and are larger in size. Additionally, the NEMA-14 is incapable of delivering the necessary torque for precise CNC operations.

TABLE 1. COMPARISON THE MAIN FEATURES OF THE PROPOSED CNC MACHINE

Reference	**[63]**	**[64]**	**Proposed system**
Main objective	To cut certain materials accurately	For PCB production or precision woodworking	Create a CNC wood carving machine with reasonable price and high accuracy for small projects
software	CAD software to draw the model and Mach3 software for programming	Autodesk Fusion 360 to draw a 3D model and UGS to input the code into the grbl library	Solidworks to design 3D model and UGS to input the G-code into the grbl library
Axle motion system	The axes work in a hierarchical order where the x-axis supports the y-axis, which in turn supports the z-axis	The x-axis is designed to be independent for flexibility in controlling machine movement	The workpiece moves in the x-axis in synchrony with the other axes, providing flexibility in movement and control
Controller	Computer, L298 dual H-bridge to determine the motor rotation direction, and L297 stepper motor controller to determine the number of steps the motor should move	Arduino, CNC shield, and A4988 drivers	Arduino Uno, CNC shield, and DRV8825 drivers

VII. CONCLUSION

Wood carving machines substantially diminish the labor required for the creation of carvings and ornaments. The extensive application of CNC technology in wood carving can enhance productivity, increase efficiency, and reduce production costs. The design of the CNC wood carving machine was successfully implemented. The proposed system demonstrated diminished complexity in its control mechanism compared to currently documented devices, alongside improved operational flexibility and coordinated axis movement. The assessment of the exhibited carving machine reveals its capacity to produce wood carvings with accuracy and elaborate designs, reliable performance, and reproducibility. Moreover, the application of this technology will lead to enhanced material efficiency and waste minimization, both of which would positively impact the environment. Experiments were performed to evaluate the efficacy of the suggested CNC wood carving machine. The findings indicated that the carved models produced by this machine exhibited a carving precision range of ±0.1 to ±0.15 mm and a carving speed of roughly 500 rpm. The proposed CNC can manufacture economical handcrafted wood curving applications, making it accessible to small businesses and entrepreneurs. It demonstrates the importance and versatility of CNC machines for diverse applications and their ability to generate multiple designs with varying dimensions and complexities.

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