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Design and Construction of a low-cost Mini CNC Machine

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ABSTRACT

This research paper describes the design and fabrication of an economical mini-CNC (Computer Numerical Control) machine, providing excellent precision for small-scale applications. The machine is constructed with economical components, including NEMA 17 stepper motors, an Arduino Uno R3, and a palm router, all assembled within a compact framework. The total construction cost is 40,448 BDT (about 338.43 USD), making the machine 81.76% less expensive than the Mega V2 CNC model and 44.23% more economical than the Onefinity CNC PRO Series. CAD modeling and 3D printing were utilized for parts manufacture, and open-source GRBL firmware was implemented for control. Performance testing indicated negligible inaccuracies, with a hexagonal design of 95 mm exhibiting an output inaccuracy of merely 0.0842%. Additional testing demonstrated comparable accuracy, with an 80 mm circle resulting in a 0.075% inaccuracy. These results validate the machine's capability to transform digital blueprints into accurately manufactured components with exceptional precision. This economical CNC system serves as an optimal alternative for educational institutions, hobbyists, and small enterprises, effectively and economically connecting conceptual design with tangible production.

1. INTRODUCTION

CNC machining is a way to make things by following a process. In this situation, computers use a particular language called programming to tell machines how and what they need to create. These codes are used for things robots make in factories or workshops. CNC (Computer Number Control) machining is a way to make things. This is done by using computers to control machines that take off parts from things being changed. This means the computer program continuously instructs these tools (like drills, mills, and lathes) to remove a section of work. This action keeps going until the wished-for thing is made (Pajaziti *et al.*, 2017). John Parsons and Frank Stulen invented the first CNC machine in 1947 (Dixit *et al.*, 2017).

In the times of the technological revolution, Computer Numerical Control (CNC) machines play integral parts in the manufacturing sector thanks to their high precision, speed, and flexibility. Miniaturized CNC systems have democratized the automated manufacturing process until recently, striving for the reserve for large-scale industrial enterprises. These mini-CNC machines have a small footprint and low cost, making them available for individuals, businesses, or educational institutions who want to bridge the gap between conceptual design and tangible reality (Abd Rahman *et al.*, 2021). The background of CNC machining is distinctive. It has evolved from the initial CNC machine that utilized punch cards to a software-driven machine requiring less supervision. CNC machining is the preeminent production process used across several industries (Sung & Carlsson, 2003). Mini CNC machines have changed the making business by giving small and cheap choices to big CNC machines. These machines keep the usefulness and accuracy of their bigger counterparts but with smaller areas for cutting (Pabolu & Srinivas, 2010).

This venture is driven by the assumption that a well-designed mini-CNC machine can compete with existing perceptions of size boundaries and thus provide an economically viable solution at equal scales to those commonly associated today as 'desktop manufacturing.' This thesis will contribute to emerging technology related to small CNC systems through systematic studies, innovative design, and thorough assessment procedures. It will outline the way for further design development, enhance the unlimited opportunities offered by small-scale manufacturing, and add helpful insight into how well we can make a mini-CNC machine.

2. MATERIALS AND METHODS

A. Design Overview of CNC

The CNC machine features an X-Y axis for frame movement and a Z-axis for the vertical linear driving of the spindle cutter. We utilize Arduino (Barrett, 2020) and an Arduino CNC shield (Veeramony & Zahid, 2022) to control the CNC machine for firmware. We use open-source, popular firmware GRBL (Sarguroh & Rane, 2018), while a computer transmits the G-code to the CNC. The utilization of stepper motors achieves precise rotations (Bangse *et al.*, 2020). The primary design criteria are functional and derived. The functional requirements constitute a collection of derived specifications essential for finalizing the machine's design (Noonan, 2012). The CNC machine primarily comprises mechanical components (including the structure, such as the base, support framework, lead screws, beams, bearings, etc.) and an electrical system (consisting of the motor, motor control unit, and power unit). It utilizes a Universal G-code Sender (UGS) to transmit G-code to the CNC machine. The choice of the motion control system and the linear motion components, facilitated by linear guideways and drive screws, is a crucial aspect of the prototype milling machine design. The screws can be operated by specific motors utilizing an open-loop control system. The CNC machine's construction comprises mechanical, driving, measurement, and control systems. The structure incorporates kinematic modules for functional systems, including supports, stands, and bearing support systems, drive systems for leading (slide and roller guides), and circular and linear motion measurement systems. We used the palm route as the primary spindle module, which has several critical functional components: the spindle shaft, housing, axially spaced roller bearings, electric drive motor, internal cooling system, and tool gripping and releasing mechanism. The principal design factors for constructing a CNC machine are:

- The workpiece's maximum dimensions (maximum movement along each axis) are X = 350 mm, Y = 550 mm, and Z = 90 mm.
- Multiple designs can be assessed for their characteristics, including increased rigidity, greater precision, operational ease, and programming efficiency.
- The machine framework, called the "backbone," incorporates all tool elements. The machine's performance fundamentally relies on its direct impact on static and dynamic stiffness and damping responsiveness. Closed-frame architectures are frequently employed in precision machinery.
- The required screw precision is 0.0007 mm, achievable with a stepper motor that has a step size of 0.125° and a lead screw pitch of 2 mm. Thus, the accuracy of the screw is determined by the formula P x (Micro-step/360°) = 2 x (0.125/360) = 0.0007 mm.

B. Materials

The construction of the mini-CNC machine required a careful selection of components to ensure cost-effectiveness while maintaining performance. The critical components shown in Figure 1 used in the construction:

- **NEMA 17 Stepper Motors:** These motors move the machine on the X, Y, and Z axes. They were chosen because they are precise and can generate high torque for consistent machine tool positioning.
- **Arduino Uno R3:** The main microcontroller used to process G-code and interface with the CNC machine. The Arduino IDE was employed to program and upload control firmware to the board.
- **CNC Shield:** To integrate motor drivers and ensure precise control of the stepper motors, a CNC shield compatible with the Arduino Uno was selected.
- **Palm Router:** A palm router was used as the spindle to cut and engrave various materials.
- **Lead Screws and Linear Shafts:** These were used to ensure smooth and accurate movement along the X, Y, and Z axes. The lead screws translated the rotational movement of the stepper motors into linear motion.
- **POM Wheels:** POM wheels provide low friction and durability and are used for smooth motion along the X-axis.
- **Stepper Motor Driver:** The A4988 Stepper Motor Driver is a widely applied module in making mini-CNC machines. It can operate step motors with a 1/16 micro step.
- **Aluminum Profiles (2040 and 2020):** Aluminum profiles were used for the structural framework, offering a lightweight and rigid design to support the machine's moving parts.
- **Power Supply (700-watt DC):** This powered the motors and electronic components, ensuring stable operation throughout the machining process.
- **SC8UU and SC12UU Ball Bearings:** These ball bearings were used to support the lead screws and ensure smooth motion with minimal friction.
- **KP08 Support Block Bearings:** These support bearings were used to stabilize the lead screw and prevent deflection, ensuring precise movement during the machining process.
- **GRBL Firmware:** An open-source firmware that controls the machine’s movements based on G-code instructions. It was uploaded to the Arduino microcontroller via the Arduino IDE.

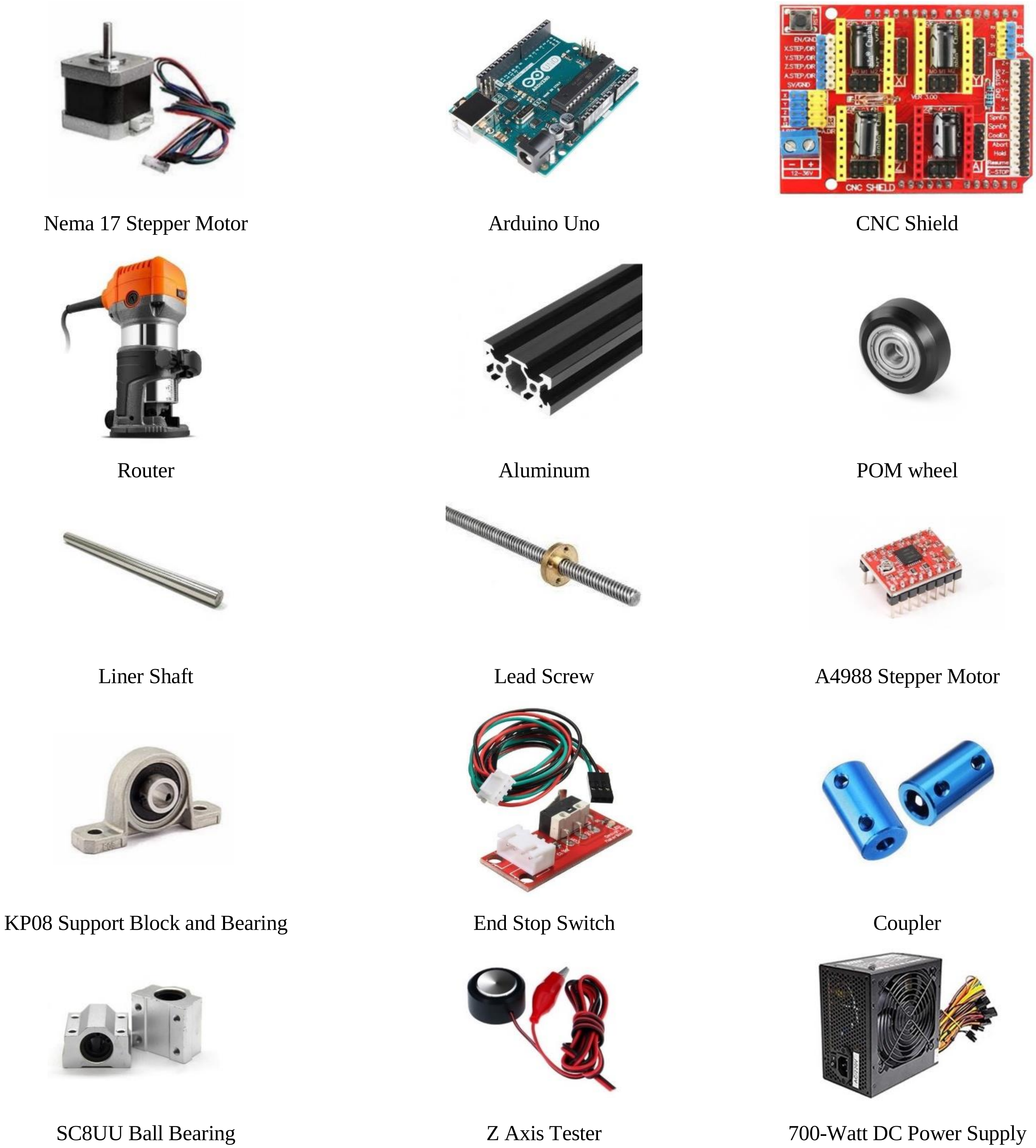

Figure 1: Components used in our CNC

C. 3D Printed Parts

SolidWorks was used to develop essential components for a Mini CNC machine because it produces exact and well-designed 3D drawings. These models were brought to life through 3D printing and became necessary parts that keep the Mini CNC operating. The parts we used in our project are shown in Figure 2.

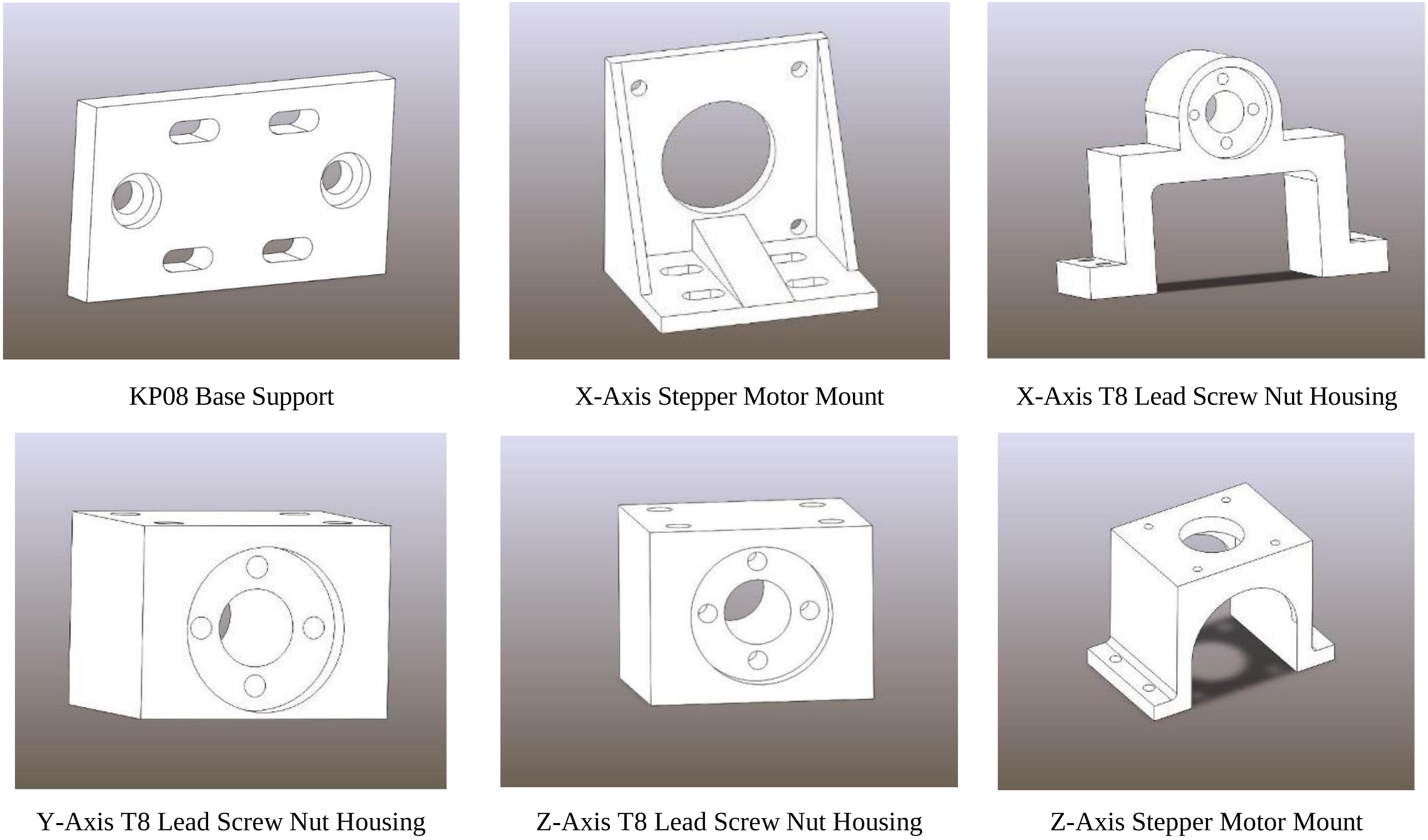

Figure 2: CAD design of our 3D printed parts

D. Circuit Diagram

Figure 3 showcases a detailed circuit diagram for the CNC machine, indicating all electrical connections among components, vital for constructing a reliable and effective electronic control system central to machine operations.

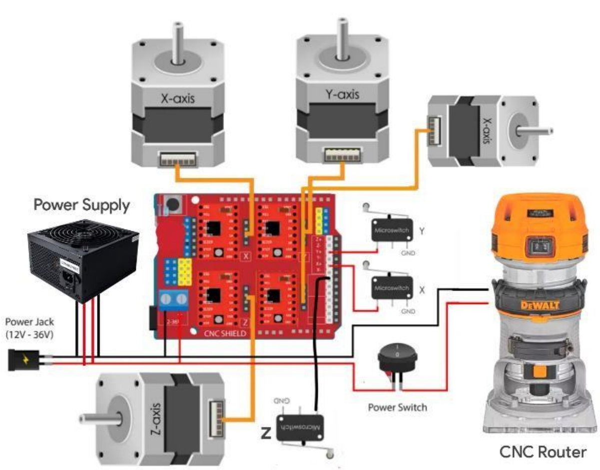

Figure 3: Circuit Diagram

3. FABRICATION AND ASSEMBLY OF CNC MILLING MACHINE

First, a detailed list of parts and components required to manufacture a mini-CNC machine was compiled, and then the process took place over time, whereby all these elements were procured. Meanwhile, a digital 3D model of the mini-CNC machine was precisely menacing and developed in SolidWorks. Many elements, incredibly portable ones, were handcrafted initially with subsequent assembly. They were made tangible by printing them through a portable 3D printer to obtain the necessary components. Our assembled mini–CNC Machine is shown in Figure 4. Our CAD Model of the mini–CNC Machine is shown in Figure 5.

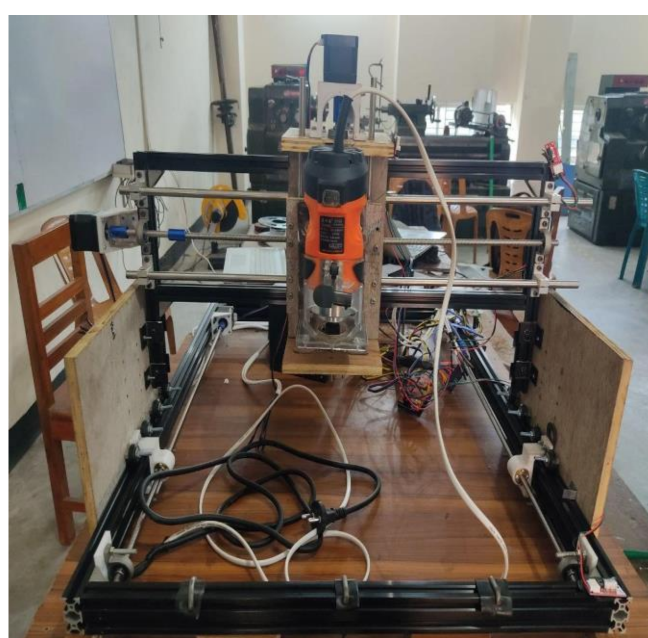

Figure 4: Assembled Mini CNC Machine

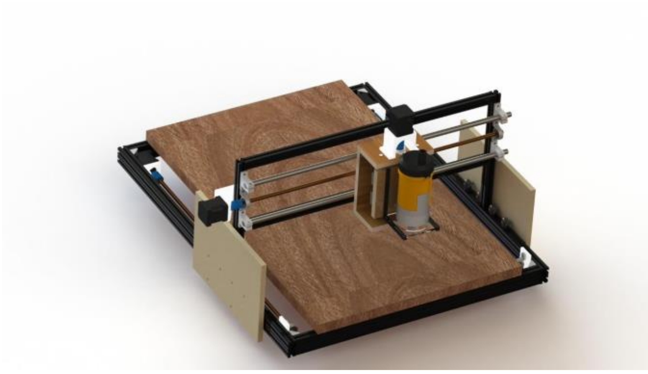

Figure 5: CAD Modeling of Mini CNC Machine

4. COST ANALYSIS

Table 1 shows how much each part of our mini-CNC machine project costs.

Table 1
Cost Analysis

Components	Price (BDT)
Stepper Motor	5160
Arduino Uno R3	1100
CNC Shield	1200
Stepper Motor Driver	1000
Palm Router	4500
Z Axis Tester	620
SC12UU Ball Bearing	1720
Wheel Pom	2060
SK12	1096
SC8UU Ball Bearing	1172
KP 08 Pillow Block Mounted	1170
SS Electric Spacer	540
2020 Aluminium Corner Bracket	960
KFL08	430
End Stop Switch	500
Culper	630
SK08	1060
Cutting Toolbox	1700
2040 Aluminium Profile (800mm)	2500
2040 Aluminium Profile (600mm)	1880
2020 Aluminium Profile (600mm)	1650
2020 Aluminium Profile (300mm)	830
Lead Screw (700mm)	2000
Lead Screw (700mm)	710
Linear Shaft Rod (700mm)	1750
Linear Shaft Rod (300)	320
Lead Screw (600mm)	900
Miscellaneous	2250
Total Cost	**40448**

The steeper motor and the router (Dharmawardhana *et al.*, 2021) are the most expensive parts of our CNC machine. The total cost of our CNC is 40448 BDT (338.43 USD based on the currency rate on September 21, 2024), and the construction cost is 1.16 USD per square inch. Our CNC machine is significantly more cost-effective compared to other models. It is 81.76% cheaper than the Mega V2 (*Mega V 2 - MillRight CNC, LLC*, n.d.), 44.23% less expensive than the Onefinity CNC PRO Series (*PRO Series Journeyman CNC Machine 48x32 Cut Area*, n.d.), 65.37% cheaper than the MillRight CNC Carve King 2 (*MillRight CNC Carve King 2 Kit| Affordable CNC Machines*, n.d.), and 47.27% more affordable than the 3 Axis CBeam CNC Machine (*3 Axis CBeam CNC Machine Mechanical Kit DIY CBeam Engraver Frame Kit | EBay*, n.d.). This makes your machine a highly competitive option in terms of price per square inch, as shown in Figure 6.

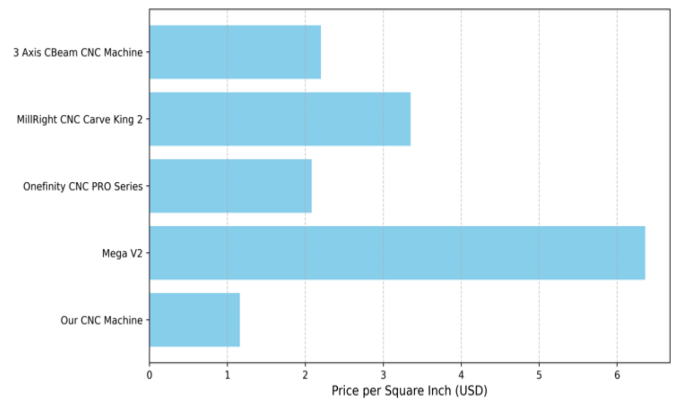

Figure 6: Cost Comparison

4. RESULTS AND DISCUSSIONS

Figure 7 illustrates the CAD design's exact dimensions, while Figure 8 verifies that the CNC output nearly adheres to these standards. The error is also calculated in Table 2. The comparison of the CAD design with the CNC machining results demonstrates a strong correlation between the specified dimensions and the resultant measurements. Indicates that the hexagonal geometry was built in SolidWorks with an outside diameter of 95 mm. However, the CNC output measured 94.92 mm, yielding a negligible error of 0.0842%. The colossal circle was intended to have a diameter of 80 mm; however, the CNC cut resulted in a measurement of 79.94 mm, yielding an error of 0.075%, which is also minimal.

Table 2
Accuracy Analysis

Parts of Design	CAD Measurements (mm)	Output Measurements (mm)	Error (%)
Hexagon	95	94.92	0.0842
Large Circle	80	79.94	0.075
Small Circle	45	44.93	0.156

The little circle was intended to be 45 mm in diameter, whereas the actual output measured 44.93 mm, resulting in an error of 0.156%, which is marginally higher. According to theoretical accuracy, it is far beyond these. The errors come from the palm router's vibration and the machine frame's lack of rigidness. The accuracy can be improved by improving the rigidness of the frame and replacing the router with a better one. However, it remains within acceptable tolerances. The modest inaccuracies underscore the overall accuracy of the CNC machining process. Only slight deviations, presumably due to machine calibration or material inconsistencies, exist. This comparison substantiates the technique's dependability in manufacturing precise components.

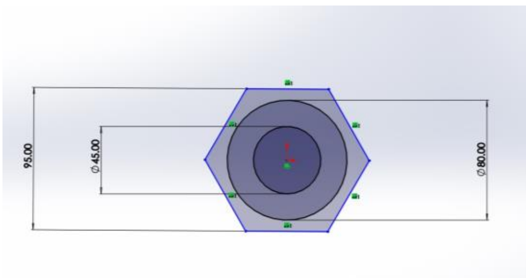

Figure 7: 2D CAD design with dimensions

Figure 8: Output Design and Taking Measurements

Figure 9 depicts the CAD design of an elephant model, which was utilized to create the toolpath for CNC machining. The design features intricate details in the elephant's trunk, legs, and body, highlighting the dimensional precision necessary for production. Conversely, the second image, Figure 10, illustrates the product manufactured by the CNC machine sculpted from a foam block.

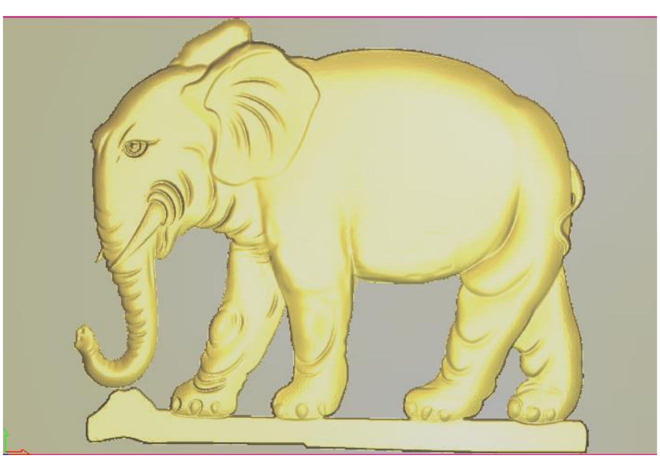

Figure 9: CAD Design of Elephant Model for CNC Machining

Although the overall shape and curves of the elephant are well-preserved, there is a discernible diminishment in the clarity of the finer details, especially in regions such as the ears and trunk, likely due to the material characteristics of the foam. The pliable characteristics of foam may have resulted in a diminution of precise detail during the milling process.

Nonetheless, the overall structure resembles the original CAD model, illustrating the CNC machine's capacity to replicate intricate patterns accurately and with commendable precision. Enhancing the machine parameters or employing a more rigid material may enhance the precision of complicated features.

Figure 10: CNC Machined Elephant Model in Foam Material

5. CONCLUSIONS (COPYRIGHT AND LICENSE)

This paper showcases the effective design and building of an economical mini-CNC machine, highlighting its cost-effectiveness and accuracy. The device excelled in transforming digital designs into tangible items, exhibiting only slight variations in output measurements, underscoring the impressive accuracy that can be attained. Even with subtle variations in specifics when handling softer materials such as foam, the machine shows significant potential for educational and small-scale production applications. Its affordability positions it as a strong contender against commercially available CNC systems, delivering substantial savings while maintaining performance standards. This initiative opens doors for new advancements in compact CNC systems, fostering creative projects and learning opportunities. Future efforts might refine material accuracy and fine-tune machine settings to elevate its efficiency in intricate production activities.

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