Abstract

This report presents the comprehensive development and integration of a CNC machine, emphasizing both its mechanical and electronic subsystems. The mechanical subsystem includes detailed configurations of motors, actuators, and the CNC framework, ensuring precision and reliability in physical operations. The electronic subsystem is driven by VHDL (VHSIC Hardware Description Language) programming, which provides precise control over hardware design and supports concurrent processes essential for real-time operations.

The report delves into the advantages of using VHDL for FPGA (Field Programmable Gate Array) programming, highlighting its flexibility and efficiency. Detailed block diagrams and flowcharts illustrate the system's overall functionality, showing the interaction between modules like the clock divider, shape selector, and multiplexer. Each shape module—square, triangle, diamond, and rectangle—was meticulously designed to manage specific geometric operations, showcasing the system's versatility.

The modular design approach adopted in this project enhances the system's scalability and maintainability, providing a robust framework for future enhancements. The integration of mechanical precision with advanced control logic underscores the complexity and innovation inherent in modern CNC technology.

This report dives in the field of CNC machine development by offering a detailed methodology and practical insights into integrating mechanical and electronic subsystems. The findings and methodologies presented here serve as a valuable reference for future research and development in CNC technology.

Dedications

I would like to express my deepest gratitude to my family, whose unwavering support and encouragement have been instrumental in the completion of this report.

To my father, thank you for instilling in me the values of hard work and perseverance. Your wisdom and guidance have always been a source of strength for me.

To my mother, your endless love and nurturing spirit have provided me with the comfort and confidence to pursue my dreams. Your sacrifices and unwavering belief in me have been my driving force.

To my two brothers, your camaraderie and support have always been a source of motivation. Thank you for being there for me and cheering me on throughout this journey.

To my sister, your kindness and understanding have been a constant source of comfort. Thank you for always believing in me and providing me with the encouragement I needed.

This report is a testament to your love and support, and I am eternally grateful for having such an amazing family by my side.

This work is dedicated to those who have been an integral part of my journey, providing endless support, inspiration, and encouragement:

To my mother, whose unconditional love, patience, and nurturing spirit have been my constant source of strength. Your faith in me has given me the courage to pursue my dreams.

To my father, whose wisdom, guidance, and unwavering support have shaped me into the person I am today. Your hard work and dedication have always inspired me to strive for excellence.

To my two sisters, who have always been there for me with their unwavering support and encouragement. Your belief in my abilities has motivated me to overcome every challenge.

To my dear friend Riad, for his steadfast friendship and for always being there to lift my spirits. Your support and understanding have been invaluable.

To Mohamed, for his camaraderie and the countless moments of laughter and joy. Your friendship has been a source of great comfort and happiness.

To Anis, for his constant encouragement and for always believing in me. Your positivity and support have made a significant difference in my life.

Thank you all for being such an indispensable part of my life. Your presence and support have made this journey not only possible but also immensely fulfilling.

Acknowledgment

Praise and glorification be only to Allah SWT, the Almighty, the most beneficent and the most merciful, whose blessing and guidance have helped us to finish this work.

We would like to express our sincere gratitude to our supervisor Dr. Benzekri who accepted to supervise us for this work, and for his inspirations, encouragement and guidance throughout our project.

Our warm thanks to all IGEE family (students, teachers, workers) who all contributed in some way to this project.

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Abbreviations List

CNC	Computer Numerical Control
EDA	Electronic Design Automation
VHDL	Very High Speed Integrated Circuit Hardware Descriptive Language
FPGA	Field-Programmable Gate Array

General Introduction

The rise of digital fabrication technologies has significantly transformed modern manufacturing processes, enabling the creation of highly precise and complex parts. Among these technologies, Computer Numerical Control (CNC) machines stand out for their versatility and precision in shaping materials. Traditionally controlled by microcontrollers or specialized processors, CNC machines have seen a paradigm shift with the integration of Field Programmable Gate Arrays (FPGAs).

FPGA-based CNC machines leverage the reconfigurable nature of FPGAs to enhance performance, flexibility, and customization in machining tasks. Unlike fixed-function microcontrollers, FPGAs allow for parallel processing, which can significantly increase the speed and efficiency of CNC operations. This parallelism, combined with the ability to tailor the hardware to specific application needs, makes FPGAs an ideal choice for sophisticated CNC machine control systems.

The design and implementation of an FPGA-based CNC machine involve several critical steps. These include developing hardware architectures for motion control, implementing precise stepper motor drivers, integrating real-time sensor feedback, and creating robust communication protocols. Additionally, sophisticated algorithms for path planning and interpolation are essential to ensure smooth and accurate tool movement.

This introduction delves into the fundamental aspects of designing and implementing a CNC machine controlled by an FPGA. It will explore the benefits of using FPGAs in CNC applications, outline the key components and architectural considerations, and discuss the potential challenges and solutions in developing such systems. By harnessing the power of FPGAs, manufacturers can achieve new levels of precision, efficiency, and adaptability in CNC machining, paving the way for advancements in various industrial applications.

Chapter 1

Introduction

1.1 Introduction

Computer Numerical Control (CNC) is a manufacturing technique that uses computer software that has been preprogrammed and incorporated into the equipment to automate the movement, control, and precision of machine tools. Figure1.1 represents what a CNC machine looks like.

Figure 1.1: Basic CNC Machine

Metal and plastic items are frequently machined in production using CNC. Common cutting instruments that can also have their operations automated by CNC include mills, lathes, routers, drills, grinders, water jets, and lasers. Additionally, non-machine tools like filament-winding machines, electronic assembling, and welding can be controlled with it.

1.2 History of CNC Machines

1.2.1 The Origin of CNC

The history of CNC machining dates back to the Second World War's pressing need. This technology developed as a result of the need for intricate and precise machinery parts, especially in the aerospace sector. Traditional methods were insufficient as the battle demanded high-quality components to be produced quickly, which prompted entrepreneurs to investigate automated solutions.

In 1952, John Parsons and Frank L. Stulen of Parsons Corporation in Traverse City, Michigan, collaborated to create the first CNC machine, an experimental milling machine.

Their primary focus was on manufacturing extremely precise helicopter blades. This early machine was a major turning point in the history of CNC machining, laying the foundation for further advancements.

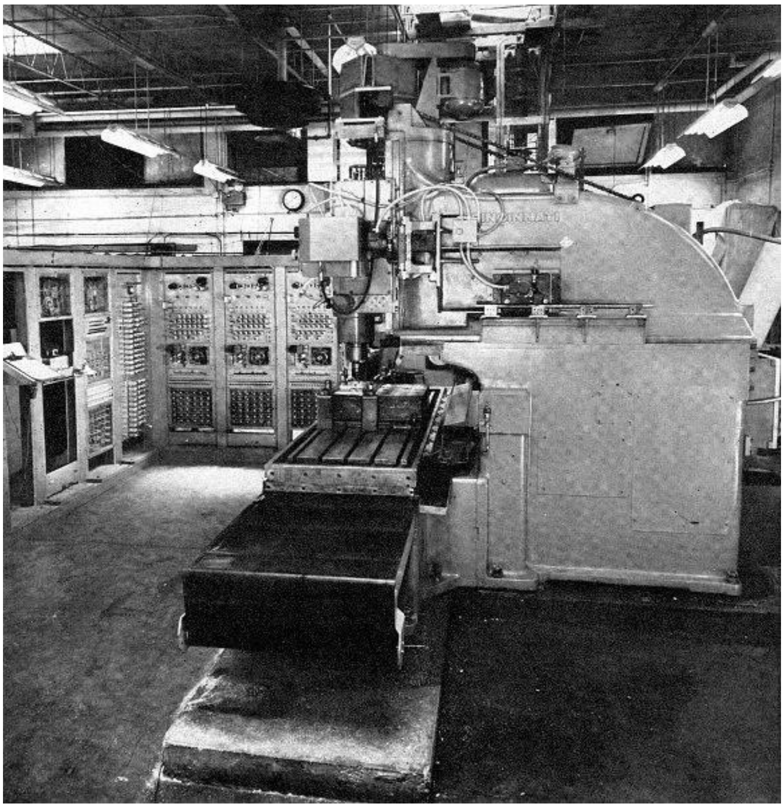

Figure 1.2: First Experimental CNC Milling Machine

Their device made use of numerical control systems and motor-controlled equipment, which are early manifestations of what is now known as CNC technology. as Figure 1.2 will show that it had a positioning machine tool, which was an early form of digital programming, that could track points entered into the system on punched tape.

The origins of CNC (Computer Numerical Control) machining can be found in the substantial technological developments and expanding manufacturing sector of the 1940s and 1950s. The idea of automated machining started to take shape at this time, setting the groundwork for a revolutionary change in production techniques.

1.2.2 Why Was The CNC Machine Developed

The requirement for increased accuracy and productivity in the production of complicated parts, particularly for the aerospace and defense industries during and after World War II, was the main force behind this evolution. In response to the shortcomings of manual machining and the growing need for high-precision components, computer numerical control was developed. A turning point in the history of manufacturing was the development of numerical control systems and motor-controlled machinery, allowing devices to carry out tasks in accordance with pre-programmed instructions.

Compared to the conventional handcrafted methods that were common before the invention of CNC machines, this automation represented a quantum leap. CNC machining was primarily developed to meet the urgent demands of the manufacturing sector, which included increased productivity, accuracy, and the capacity to create intricate geometric shapes. Manufacturing techniques were drastically changing throughout the Second Industrial Revolution, and CNC technology developed as a response to the growing need for high-quality parts in sectors including consumer electronics, automotive, and aerospace.

The following particular requirements prompted the development of CNC machines:

- the need for intricate pieces to be mass-produced with exacting tolerances.
- the requirement for manufactured items to have constant quality and accuracy.
- decrease in human error linked with manual labor in machining operations.
- Growing industrial and consumer demands are driving up production rates.

1.2.3 Pioneers of CNC Machining

Visionaries who anticipated the effects of automated control systems in production were the forerunners of CNC machining. Important numbers consist of:

- John T. Parsons [1]: Often hailed as the originator of computer numerical control (CNC) machining, Parsons was the brains behind the application of numerical control in machine tools. He worked with the Massachusetts Institute of Technology (MIT) to create the first machine tools that could be controlled numerically as Figure1.3 will show. Many honors, including those from manufacturing engineers' groups, have been given to him in recognition of his contributions to the fabrication of intricate aerospace components and helicopter blades.

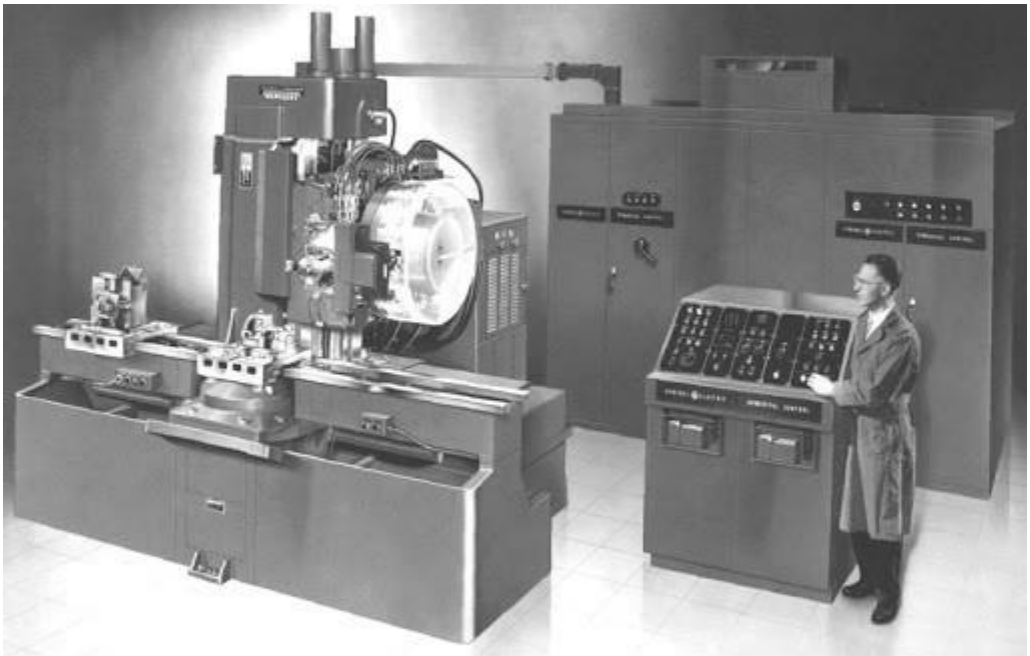

Figure 1.3: John T Parson

- Frank L. Stulen [1]: Stulen, who collaborated with Parsons, was instrumental in improving the idea of numerical control. His creative thinking and technical proficiency were crucial to the real-world implementation of Parsons' concepts, resulting in the development of the initial CNC machine prototypes.

Through their joint efforts, the first CNC machine—an experimental milling machine with previously unheard-of levels of precision and complexity—was created. Punch tape technology, an early form of digital programming, was employed to control the functions of this early device. Due in large part to the project's success, the U.S. Air Force provided funding for additional research and development, which sped up the development of CNC technology.

1.2.4 Timeline of CNC Machining

- **1940s: The Idea's Origins**: The initial conceptualization of CNC machining occurred in the 1940s. The Second Industrial Revolution, which put an emphasis on automation and efficiency in manufacturing processes, defined this era.

  John T. Parsons, a creative engineer, started developing the idea of numerical control for machine tools during this decade. His groundbreaking concepts established the foundation for a new chapter in manufacturing history.

  Parsons imagined a system that would drastically differ from the manual operations that were common at the time by allowing the movements of machine tools to be controlled by a series of coded instructions. This idea served as a model for contemporary computer numerical control (CNC) technology, which enables accurate and automated machining operations.

- **Late 1940s: Initial Trials**: The concepts of Parsons started to take shape in the late 1940s. They started working together with Frank L. Stulen to improve the idea of numerical control. Their innovative experiments resulted in the creation of prototypes that revolutionized the manufacturing industry.

  One of their main initiatives was creating an effective way to make helicopter blades. The precision and repeatability needed for this task were beyond the capabilities of traditional machining techniques.

  Their research in this field demonstrated not only that numerical control is feasible but also that it has the potential to completely transform manufacturing capabilities.

- **Late 1950s: The Start of Commercialization:** A new era in manufacturing began with the commercialization of NC machines towards the end of the 1950s. Being among the first to sell NC machines on a commercial scale, businesses such as Giddings and Lewis Machine Tool Co. became leaders in this field. Around this time, the manufacturing sector began to change as more businesses began to realize the benefits of CNC technology.

  Manufacturing capabilities saw a radical shift with the commercial availability of NC machines. Businesses started implementing these devices to improve their manufacturing procedures, reaping the advantages of higher accuracy, lower labor expenses, and easier production of intricate components.

- **1967: First CNC milling machine:** Another significant development in the history of CNC machining happened in 1967 when the Electronic Data Control Company unveiled the first real CNC milling machine. This development greatly increased the potential of CNC machining and created new avenues for the production of intricate and complex parts.

  A major advancement over previous models, the first CNC milling machine featured sophisticated features like computerized programming, accurate control over multiple axes, and the capacity to execute intricate cuts and movements. This device served as a prototype for subsequent CNC technology advancements and was instrumental in the technology's broad industry adoption.

- **1970s: Microprocessors and Cost Reduction:** With the introduction of microprocessors, CNC machining entered a new era in the 1970s. The creation of more compact and reasonably priced CNC machines was facilitated by these compact yet potent parts, greatly increasing their availability. It is impossible to overestimate the contribution microprocessors made to CNC technology; they transformed control systems and increased the dependability and efficiency of CNC machines.

  Smaller manufacturing facilities and educational institutions, which previously found the size and cost of CNC machines prohibitive, benefited greatly from this advancement. Microprocessors made it possible to create small, reasonably priced CNC machines, which democratized technology and spurred fresh innovation across a range of sectors.

1.3 Types of CNC Machines

1.3.1 Router CNC Machine

A router CNC machine is distinguished by its capacity to design and shape materials such as steel, aluminum, plastic, foam, composites, and wood using computer numerical control to route spindle and machine tool paths.

A mechanical base, spindle, controls, power supply, stepper motors, and stepper drivers are typically found in CNC routers as illustrated in Figure 1.4. It also speeds up product production, lower waste, and boost accuracy and productivity.

Figure 1.4: Router CNC Machine

1.3.2 Drilling CNC Machine

Drilling creates cylindrical holes in the work piece by using rotating drill bits. The design of the drill bit permits the waste metal, or chips, to separate from the work piece. Drill bits come in several varieties, each intended for a particular purpose. Drill bits come in several varieties, such as chucking reamers, peck drills, screw machine drills, and spotting drills. Figure 1.5 showcases what a Drill CNC looks like.

Figure 1.5: Drill CNC Machine

1.3.3 Lathe CNC Machine

In turning, material is removed from the rotating work piece using single-point cutting instruments as shown in Figure 1.6. There are several turning tool designs for different uses, including as roughing, finishing, facing, threading, shaping, undercutting, parting, and grooving.

Lathes or turning machines with CNC capabilities are also used in the CNC turning process. Turret lathes, engine lathes, and special-purpose lathes are among the varieties of CNC lathes.

Figure 1.6: Lathe CNC Machine

1.4 Open and Closed-Loop CNC Machining

An open loop or closed loop system controls how a material is manipulated on a CNC machine. A closed loop system may take feedback and remedy any problems that may occur, such as material location or feed speed, while an open loop system just operates in one direction until the process is finished.

The simplicity of an open loop control system depends on how accurately it is calibrated. After material is supplied into the system, a finished product is given back. Although there are no in-process adjustments, human error must be prevented by carefully and painstakingly completing the calibration. A washing machine is a good example of an open loop system; garments are loaded into the machine and taken out once they are well cleaned. The machine doesn't pause to make adjustments or assess whether the clothes are clean enough.

Compared to an open loop system, a closed loop system is more sophisticated and depends on the controller. A closed loop system has an amplifier, controller, and receives feedback during operation, whereas an open loop system has a controller process. This is demonstrated by a home's heating system, which turns on when a predetermined temperature is not met and turns off or modifies itself when the temperature is appropriate. A closed loop system functions more slowly and cautiously due to continuous process monitoring, but it is simple to calibrate because the system bears the majority of the burden.

Multiple axis points are referenced by CNC equipment in order to remove material from the work-piece. There can be three, four, or five axes, depending on the situation. When the material is being worked by the machine, which moves along an XYZ plane, it stays in the same location with the basic three axis points. The four axes points add a fourth action, which could involve producing a unique cut or drilling a hole, and function in the same way as the three axes approach. Compared to the other two methods, the five axes points technique is more intricate. It is applied to extremely intricate and technological components and manipulates the material on five sides.

1.5 Applications of CNC Machines

1.5.1 Aerospace Industry

CNC machining and the aerospace sector have grown together. Actually, the needs of the aerospace sector have been crucial in shaping the development of CNC machining techniques. Robust materials are continuously being developed by the aerospace industry to build devices and other apparatus.

The majority of this equipment is concerned with things like quality assurance and safety. Precision machining is therefore unquestionably necessary. CNC machining effectively completes the checklist.

1.5.2 Automotive Industry

One of the primary markets for CNC machining is the automobile industry. Every step of the automobile manufacturing process benefits from CNC machining, from large-scale part production to research and development (R and D) prototypes.

Furthermore, CNC milling machines and lathes are used to create a wide range of components, from tiny gears and panels to huge engine block pieces. In the automotive industry, these machines operate with both metal and plastic materials.

Just one combustion engine requires numerous CNC machining procedures. These include fabricating cylinders, pistons, and other components that make up the cylinder assembly in the engine block, as well as transforming massive metal blocks—typically made of aluminum—into engine body panels.

1.5.3 Electronics Industry

Similar to the automobile sector, the electronics industry also uses CNC machining for manufacturing and prototype. One of the benefits of CNC machining for electronics is its consistent handling of small-scale fabrication.

The metal alloy housing of Apple devices, such as the Macbook and iPhone, is a prominent example of CNC machining in electronics. CNC routers and milling machines are used to make these. CNC is applicable to both the internal and external parts of consumer electronics items.

1.5.4 Military and Defense Industry

The aerospace and military sectors have criteria that are comparable to each other. These sectors produce a wide range of novel materials and sophisticated technology, which calls for complex machinery rather than basic pieces.

CNC systems find wide-ranging applications in many fields, ranging from complex, specialized weapon body designs to internal missile component manufacturing.

1.5.5 Healthcare Industry

The fact that CNC systems are utilized in the healthcare industry can come as a surprise. Nonetheless, there are many uses for CNC machining in the medical and healthcare sectors.

Rapid tooling to build dies for injection molding and the production of medical supplies are two applications for CNC machining in the healthcare and medical sector. Then, apparatus like face masks are made via the injection molding method.

Other essential specifications for instruments used in the healthcare sector are precisely smooth surface finishes. Many of these, like plates and screws for the bone, are placed within the body of the patient and stay there. As a result, it’s critical to guarantee that the patients have no discomfort.

1.6 Literature Review

CNC (Computer Numerical Control) machining has been the subject of extensive research due to its impact on manufacturing processes. Researchers have focused on various aspects such as technological advancements, material applications, process optimization, and industrial applications.

- In 2003, Yang and Xu [2] examined the evolution of CNC technology, highlighting the transition from simple numerical control to sophisticated CNC systems. They emphasized the importance of computer integration in enhancing machine tool capabilities. Kundrák et al. (2012) further explored advancements in multi-axis machining and tool path algorithms, which have improved the precision and efficiency of CNC operations.
- In 2016, Brecher et al. [3] studied the impact of CNC machining on different materials, emphasizing improvements in cutting tool materials such as carbide and diamond coatings. These advancements have enabled the machining of harder and more abrasive materials with better surface finishes and extended tool life.
- Research by Choudhury and Bajpai [4] in 2016 which focused on optimizing CNC machining processes, particularly in the application of cutting fluids. They investigated various fluid application techniques to enhance cooling and lubrication, thereby improving tool life and work-piece quality. Additionally, studies on high-speed machining and adaptive control systems have contributed to more efficient and accurate manufacturing processes.
- in 2014, Stjernstoft et al. [5] explored the application of CNC machining in the aerospace industry, noting its critical role in producing high-precision components such as turbine blades and structural parts. The medical industry also benefits from CNC technology, as highlighted by Thilmany (2010), with its use in manufacturing implants and surgical instruments with stringent accuracy requirements.

1.7 Conclusion

In conclusion, the first chapter of this report has provided a comprehensive overview of CNC (Computer Numerical Control) machines, highlighting their origins, technological advancements, and diverse applications. The evolution of CNC technology from its inception during World War II to the sophisticated systems in use today underscores its transformative impact on manufacturing processes. Key pioneers such as John T. Parsons and Frank L. Stulen laid the groundwork for this revolutionary technology, enabling precise, automated control of machine tools.

The development of CNC machines was driven by the need for increased accuracy, efficiency, and the ability to produce complex geometric shapes, particularly in high-demand sectors such as aerospace, automotive, and electronics. The advancements in CNC machining have been supported by continuous research and innovation, as evidenced by studies focusing on material applications, process optimization, and the integration of advanced control systems.

The applications of CNC machines span various industries, from aerospace and automotive to electronics and healthcare, demonstrating their versatility and critical role in modern manufacturing. The distinction between open and closed-loop systems further illustrates the technological sophistication and adaptability of CNC machining.

Overall, the introduction and historical context provided in this chapter set the stage for a deeper exploration of the specific CNC machine being developed in this report, establishing a solid foundation for understanding its significance and potential impact on manufacturing processes.

Chapter 2

Theoretical Background

2.1 introduction

The development of simple CNC (Computer Numerical Control) machines is an exciting project that merges engineering, electronics, and software development to create versatile and accurate manufacturing tools. While advanced CNC machines can be complex and costly, basic CNC machines can be made relatively inexpensively, making them accessible to amateurs, academics, and small manufacturers.

Understanding the costs and resources involved in a simple CNC machine is essential for effective planning and budgeting. The primary components of a CNC machine are the frame, motor, control electronics, and software. Each component plays a crucial role in the machine's performance and accuracy.

By carefully selecting cost-effective materials and accessories, simple CNC machines can be designed and built to offer satisfactory performance without high costs. This introduction aims to outline the cost and material requirements, providing a basis for a detailed system analysis and implementation process. Building a CNC machine can be a feasible and rewarding project for both enthusiasts and professionals.

Figure 2.1 illustrates a block diagram showing the major parts of a CNC machine, including the frame, which is the mechanical part, and the electronic part, as well as the Quartus II EDA.

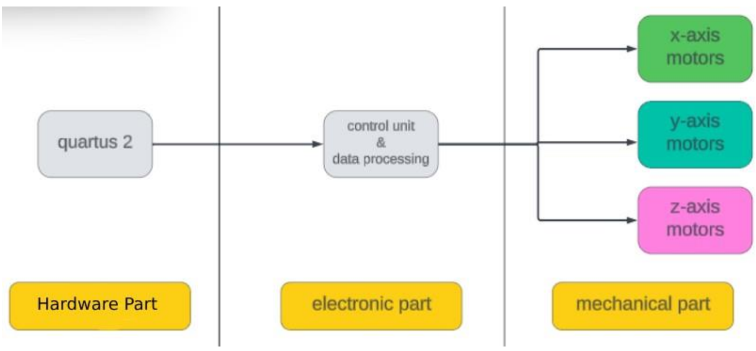

Figure 2.1: Block Diagram of CNC Machine Components

This diagram provides a clear overview of the essential components involved in the construction and operation of a simple CNC machine, emphasizing the integration of mechanical and electronic systems along with the software interface.

2.2 Mechanical Structure(Frame)

The physical aspect of a CNC (Computer Numerical Control) machine plays a pivotal role in its functionality and directly impacts its price. Important mechanical elements include the structure, systems for linear movement (like rails and bearings), screws for motion conversion, and the spindle. The structure, usually made of aluminum or steel, provides the strength and steadiness to handle machining pressures and ensure precise movements. A robust structure minimizes deflections and maintains alignment, which is essential for producing accurate parts. Systems for linear movement, such as linear rails and bearings, guarantee smooth and precise machine axis movement, which is critical for maintaining tight tolerances during machining operations.

Screws, such as lead screws or ball screws, are essential for converting rotational motion from the motors into precise linear motion. The choice between lead screws and ball screws can affect both the cost and performance of the CNC machine, with ball screws generally offering higher precision and efficiency but at a higher price. The spindle, which rotates the cutting tool, needs to be exceptionally sturdy and able to maintain consistent speeds under varying loads to ensure a high-quality finish on the machined parts.

Quality mechanical parts help reduce vibrations and deviations, leading to higher accuracy and better surface quality of machined components. These parts include precision-ground linear guides, backlash-free ball screws, and high-rigidity spindles. However, these high-quality components significantly add to the machine's cost. A well-designed mechanical system, though potentially more expensive, enhances the machine's performance, dependability, and durability, providing greater long-term value by reducing maintenance needs and boosting productivity. Investing in superior mechanical elements is crucial for achieving reliable, high-performance CNC machining, ultimately leading to more efficient production processes and higher-quality finished products.
The Figure 2.2 shows the Mechanical Structure of Our CNC Machine.

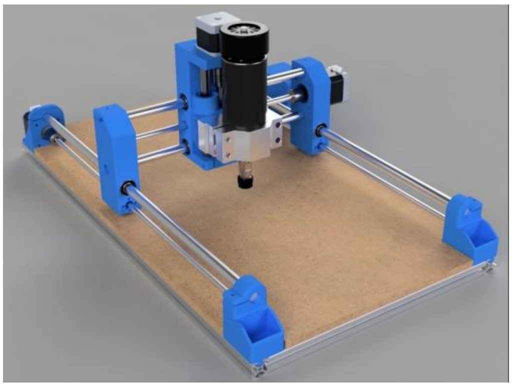

Figure 2.2: Mechanical Structure of Our CNC Machine

2.2.1 CNC Frame Mechanical Parts

The frame of a CNC machine is arguably its most critical component, as it provides the structural integrity necessary for accurate and reliable operation. It supports all the mechanical and electronic elements, including the motors, spindles, and control boards, and ensures that these components remain rigid and aligned during operation. In this introduction, we will explore the major parts of the CNC machine frame, highlighting their roles, materials, and design considerations that contribute to the overall performance and efficiency of the machine. By understanding the importance of each element, we can appreciate how a well-constructed frame lays the foundation for precise machining and robust durability.

2.2.2 Screw Rods (Lead Screws)

Screw Rods (Lead Screws) Screw rods are long threaded rods that convert the rotational motion of the motors into linear motion of the machine's axes. These components are crucial for the precise movement and positioning of the CNC machine.

Lead Screws:

Description: Lead screws are typically made from a single piece of metal with a helical thread running along their length. Function: When the motor rotates the lead screw, the threaded nut attached to the moving part of the machine travels along the screw, translating the rotational motion into linear motion.

Advantages: Lead screws such as the ones shown in Figure 2.3 are cost-effective and provide adequate precision for many applications. They also offer good resistance to back-driving, which can help maintain position when the motor is not powered.

Figure 2.3: Lead Screw

2.2.3 Gantry

The gantry typically consists of a horizontal beam (or beams) supported by vertical supports at either end. This structure allows the gantry to move along one of the primary axes of the machine, usually the Y-axis, although in some designs it may move along the X-axis. The tool head or spindle is mounted on the gantry, which allows it to traverse the workspace.

Function: Support and Stability: The primary function of the gantry is to support the tool head and ensure its stable, precise movement across the workspace. The dual-motor setup on the Y-axis, commonly seen in gantry designs, helps to evenly distribute the driving force, preventing any skewing or misalignment.

Movement: The gantry moves along the Y-axis (or X-axis, depending on design), driven by motors connected to screw rods or belts. This movement allows the tool head to position itself accurately over the workpiece.

Versatility: By moving the tool head in conjunction with the X and Z axes, the gantry enables the CNC machine to perform complex and precise machining operations on various materials.
The Figure 2.4 shows a Gantry for a 3 axis CNC machine .

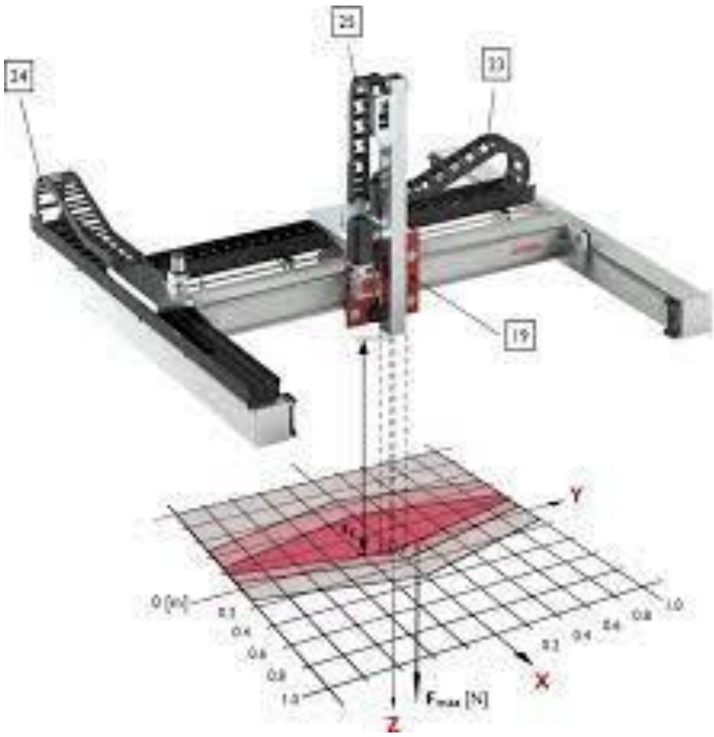

Figure 2.4: gantry

2.3 Stepper-Motors

Stepper motors are a fundamental component in CNC (Computer Numerical Control) machines, providing precise control over movement by converting electrical pulses into discrete mechanical steps. One of the most commonly used stepper motors in CNC applications is the NEMA 17. The NEMA 17 stepper motor, named for its standardized 1.7 x 1.7-inch face-plate, is favored for its balance of size, torque, and cost-effectiveness. It offers reliable and accurate positioning, making it ideal for driving the X, Y, and Z axes in CNC machines. These motors are capable of maintaining precise control without feedback systems, which simplifies the design and reduces costs. The NEMA 17's versatility and robust performance make it suitable for a wide range of CNC applications, from 3D printers to small milling machines, ensuring that the machine's movements are both accurate and repeatable. Its widespread use is a testament to its reliability and efficiency in translating digital commands into physical movements, which is essential for the intricate tasks performed by CNC machines.
figure 2.5 shows a Bipolar stepper motor that we used in our CNC machine
in the other hand the table in Figure 2.6 illustrate the Full step sequence of stepper motor .
Moreover Figure 2.7 represent the Internal structure of a generic stepper motor

Figure 2.5: Nema 17 Bipolar stepper motor

2.4 Electronic Parts

2.4.1 Field Programmable Gate Arrays

A field-programmable gate array (FPGA) is a configurable integrated circuit that can be repeatedly programmed after manufacturing. FPGAs are a type of programmable logic device (PLD) consisting of programmable logic blocks connected by a grid that can be configured to perform various digital functions. They are commonly used in low-quantity production, research and development, and applications where creating custom circuits is impractical. Industries such as telecommunications, automotive, aerospace, and industrial sectors utilize FPGAs for their flexibility, high-speed signal processing, and parallel processing capabilities.

Step N°	X	$\overline{X}$	Y	$\overline{Y}$	Angle
1	0	1	0	1	0.0°
2	1	0	0	1	1.8°
3	1	0	1	0	3.6°
4	0	1	1	0	5.4°
5	0	1	0	1	7.2°

Figure 2.6: Full step sequence of stepper motor

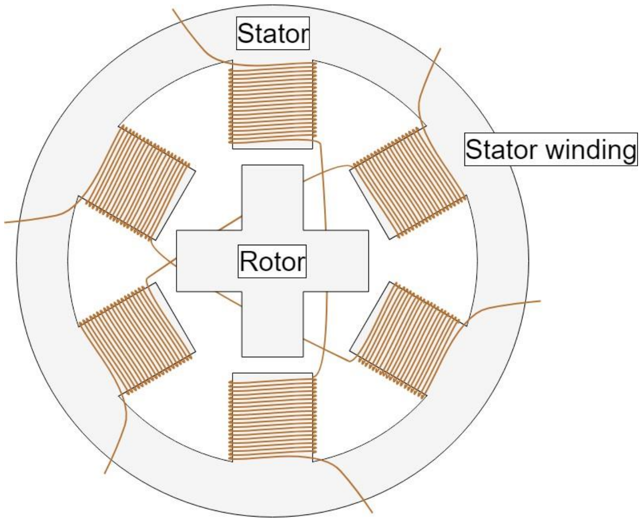

Figure 2.7: Internal structure of a generic stepper motor

FPGA configurations are typically written using hardware description languages (HDLs) like VHDL, similar to those used for application-specific integrated circuits (ASICs). The logic blocks in an FPGA can execute complex combinational functions or act as simple logic gates, and often include memory elements such as flip-flops or more advanced memory blocks. Many FPGAs can be reprogrammed for different logic functions, enabling flexible re-configurable computing.

In embedded system development, FPGAs are valuable for allowing concurrent hardware and software development, early system performance simulations, and iterative design testing before finalizing the system architecture.
The Figure 2.8 shows a Field Programmable Gate Array

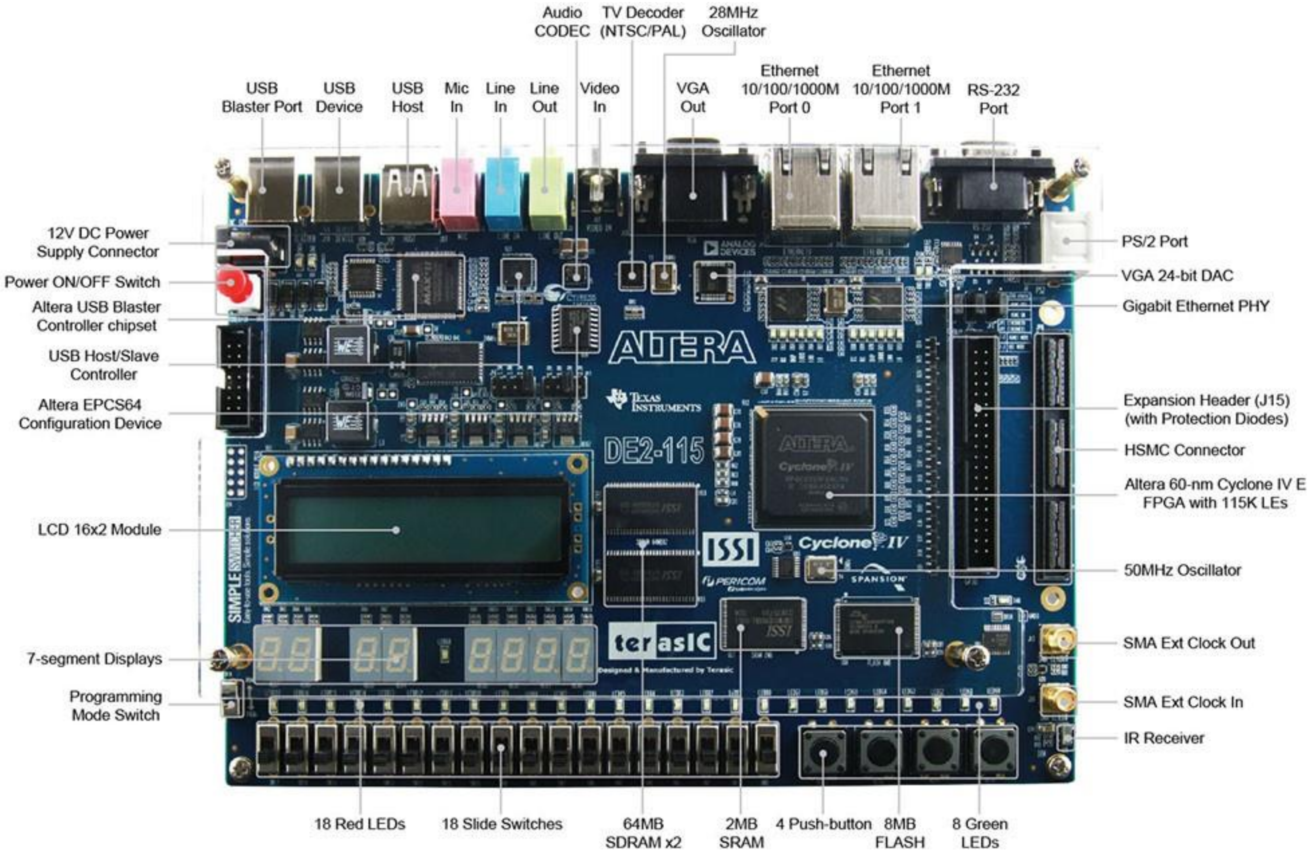

Figure 2.8: Field Programmable Gate Array [FPGA]

2.4.2 CNC Shield

The CNC Shield V3 is an expansion board designed specifically for the Arduino Uno, aiming to make it easier to build and control CNC (Computer Numerical Control) machines This shield contains various components needed to operate Arduino and CNC machines, e.g stepper motors, spindle motors, end-stop switches etc. Acting as a bridge between Offering a well-structured and simple interface, CNC Shield V3 greatly simplifies the wiring and installation process, making it accessible to amateurs and beginners alike. In addition, the CNC Shield V3 can also be used without an Arduino, making it a versatile tool for CNC applications.

The Figure 2.9 shows a CNC Shield V3

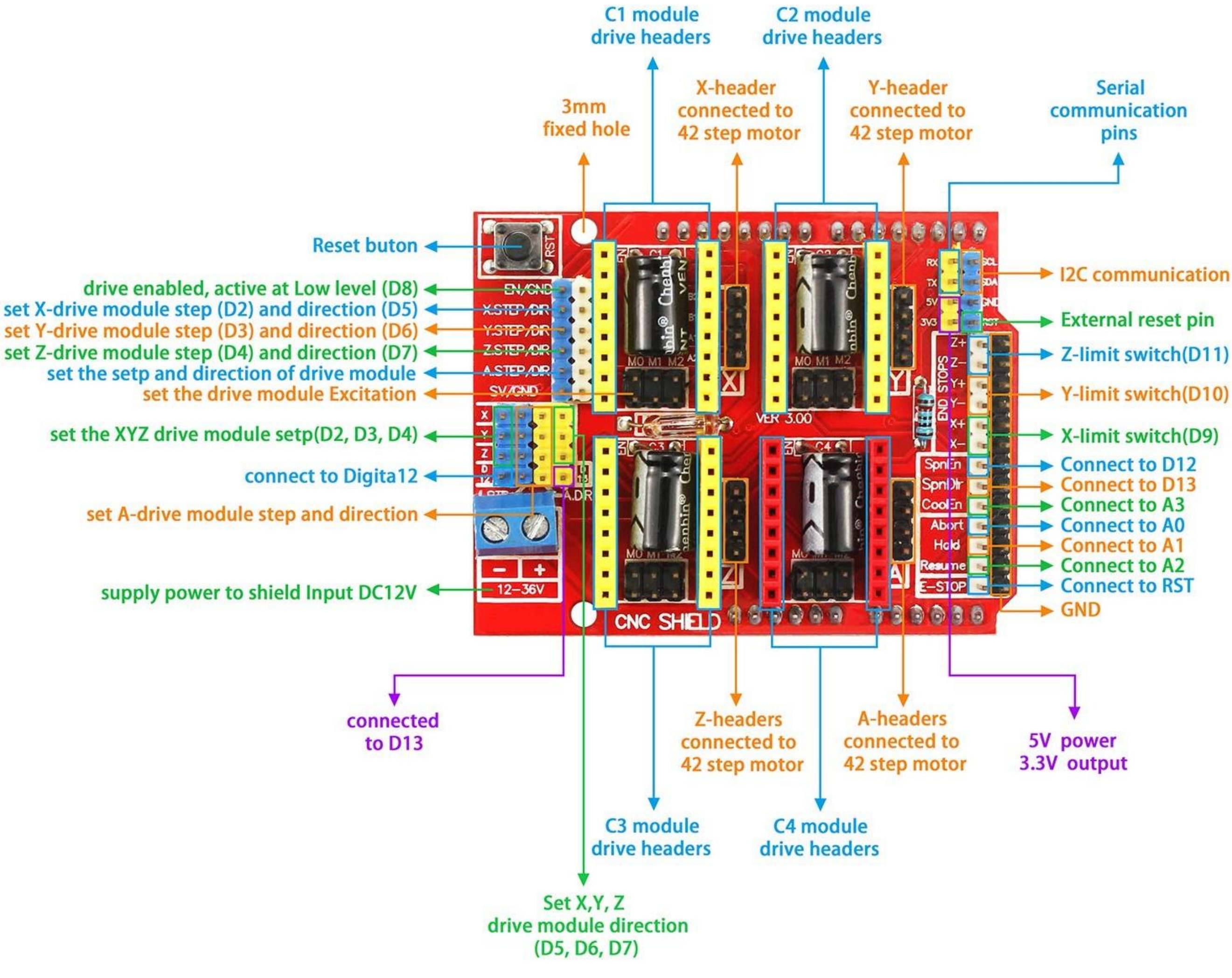

Figure 2.9: CNC Shield V3

2.4.3 Steeper-Motor Driver A4988

The A4988 stepper motor driver as illustrated in Figure 2.10 is a compact and versatile micro-phase driver designed as bipolar stepper motors. It is widely used in applications that require precise and smooth handling Control, such as 3D printers, CNC machines, and robots. The A4988 driver has an adjustable current limiting, overheating lockout, and crossover current protection, ensuring durability and reliability For a variety of demanding environments. With a power supply that works from 8V to 35V and delivers up to 2A For each coil, the A4988 supports full-step, half-step, four-step, eight-step, and sixteen-step turns, . Movement of the machinery is closely controlled. Plus, it includes an on-board potentiometer Easy adjustment of the current output according to the motor's needs, adding to its versatility. The The weakness of the A4988 to connect to microcontrollers, such as the Arduino , is its simple interface are essential features for manufacturers and engineers seeking to implement precision stepper motors control of their businesses.

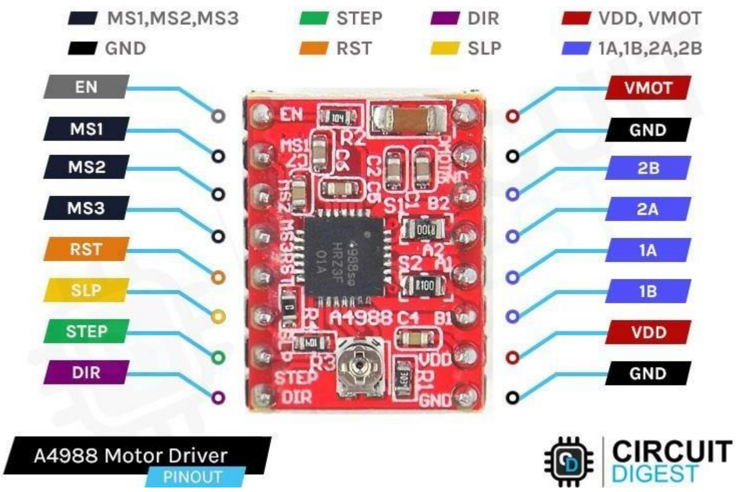

Figure 2.10: Stepper-Motor Driver A4988

Features and Benefits

- Synchronous rectification for low power dissipation
- Crossover-current protection
- 3.3 and 5 V compatible logic supply
- Thermal shutdown circuitry
- Short-to-ground protection
- Shorted load protection
- Five selectable step modes: full, 1/2, 1/4, 1/8, and 1/16

2.4.4 Octal Buffer/Line Driver with 3-State Outputs

An octal buffer/line driver with 3-state outputs is a specialized integrated circuit (IC) designed to manage the flow of data between different parts of a digital system. Featuring eight (octal) input and output lines, it serves as an intermediary that can isolate and buffer signals, ensuring robust data transmission and preventing signal degradation over longer distances or through multiple stages of circuitry. The inclusion of 3-state outputs is particularly significant, as it allows each output to exist in one of three states: high, low, or high-impedance (high-Z). The high-impedance state effectively disconnects the output from the circuit, enabling multiple devices to share the same output lines without interference. This functionality is essential in bus-oriented systems, where multiple components need to communicate over a common set of lines. Octal buffers/line drivers with 3-state outputs are widely used in applications such as memory interfacing, data buses, and microprocessor systems, providing flexibility, increased signal integrity, and efficient control of data flow.
The Figure 2.11 shows Octal Buffer/Line Driver with 3-State Outputs IC

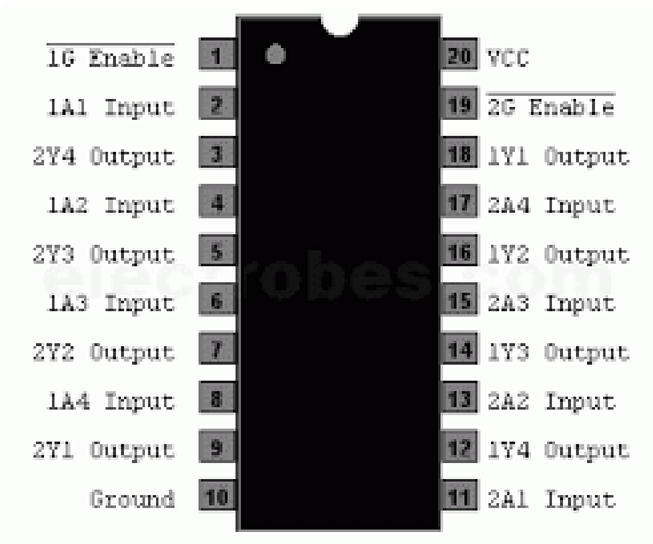

Figure 2.11: Octal Buffer/Line Driver with 3-State Outputs IC

2.5 Development Suite Tool

The control system plays a central role in the creation and use of the CNC machines, especially when it is complemented with features such as FPGAs. For our project, we employ the Quartus II Integrated Development Environment (IDE) by Intel, which is crucial for designing the FPGA control system for the CNC machine.

2.5.1 Functionality of Quartus II EDA

Design Entry and Synthesis:

Design Entry: Quartus II supports various methods for design entry, including schematic capture, VHDL, Verilog, and SystemVerilog. This flexibility allows designers to use their preferred language or methodology to describe the hardware functionality. Synthesis: The EDA includes powerful synthesis tools that convert the high-level design descriptions into optimized gate-level representations. This process ensures that the design meets the performance and resource constraints of the target FPGA. Simulation and Verification:

Simulation: Quartus II integrates simulation tools that enable designers to test and verify the functionality of their designs before implementation. Functional simulation checks the logic of the design, while timing simulation verifies that the design will operate correctly at the desired clock speeds. Verification: The environment provides extensive support for formal verification and debugging, including signal monitoring, breakpoints, and real-time data capture, which are essential for validating complex designs. Compilation and Optimization:

Compilation: The compilation process in Quartus II involves several stages, including synthesis, fitting, assembly, and timing analysis. Each stage is crucial for ensuring that the design will fit into the FPGA and meet all specified requirements. Optimization: Quartus II includes advanced optimization algorithms that enhance performance and reduce resource usage. This is particularly important for CNC applications where efficient real-time processing is critical. Programming and Configuration:

Programming: Once the design is compiled and verified, Quartus II facilitates the programming of the FPGA through various methods, including JTAG and passive serial configurations. Configuration: The EDA supports configuration management, allowing designers to manage different versions of their designs and configurations easily.
The Figure 2.12 shows the quartus 2 icon.
The Figure 2.13 shows the quartus 2 Landing page.

Figure 2.12: Quartus II Icon

Figure 2.13: Quartus II Icon Landing page

2.6 Conclusion

In this chapter, we explored various aspects of CNC machine design, focusing on the critical elements that contribute to their functionality. We examined the robust mechanical design, including components like the frame, screw rods, and gantry, which provide the necessary stability and accuracy for high-quality machining. The importance of selecting appropriate materials and components to maintain structural integrity and efficiency was emphasized.

On the electronic side, we discussed the integration of stepper motors, FPGA, and control shields like CNC Shield V3, highlighting the synergy between hardware and software. Stepper motors ensure precise movement control, while FPGAs offer flexibility and speed for real-time control. The Arduino CNC Shield V3 facilitates straightforward interaction among these components, regardless of operation complexity.

Software is also crucial, converting design blueprints into precise executable commands. The use of FPGAs allows for customization and efficiency, essential for modern CNC applications and rapid prototyping.

Overall, this chapter provided a comprehensive overview of the hardware and software elements of a CNC machine. Understanding the interplay between these components highlights the precision engineering involved in CNC systems. This foundation prepares us to refine and integrate these elements further in our project, enhancing our design and contributing to CNC technology advancement.

Chapter 3

System Design and Implementation.

3.1 Introduction

In this chapter, we will be constructing the final CNC machine using the components and techniques discussed in Chapters 1 and 2. From assembling the frame to integrating the electronic parts, each step of the process will be covered in detail. We will start with the mechanical assembly and proceed to the installation of motors, drivers, and controllers. Finally, we will configure the hardware description language to ensure seamless operation of the CNC machine. This comprehensive guide will bring together all the knowledge acquired so far to build a fully functional CNC system.

3.2 CNC Prototype Architecture

Our system can be divided into three sub-systems. As depicted in Figure 3-1, the mechanical sub-system receives necessary control signals from the electronics sub-system, resulting in the desired actuation of motors. The electronics sub-system receives commands from the software sub-system and generates controls for the mechanical sub-system.

The Hardware sub-system, using Quartus II, generates the necessary signals with an Altera Cyclone 4 FPGA as the controller. These signals are then sent to the electronics part, which consists of the stepper motor drivers and the CNC shield. Dividing the system reduces dependency between hardware and software components and allows modifications to any sub-system without affecting the rest.

In our project, we use a CNC machine with three axes (X, Y, and Z). Each axis has one stepper motor, except for the Y-axis, which has two stepper motors due to its longer length. We use A4988 stepper motor drivers to control each motor, with four drivers placed on a CNC shield V3 to ensure efficient and minimalistic hardware cabling. The Altera Cyclone 4 FPGA generates the control signals, which are routed through the CNC shield to the drivers and ultimately to the motors.

3.3 Mechanical Sub-System

The goal of the project is to develop a three-axle CNC machine with fewer parts, better durability, and a lower price. The product is cheap due to its design yet it is very solid and precise.
The body of the CNC machine is made from highly sturdy 20×20 aluminum frames, ensuring the rigidity of the construction and the entire equipment. Aluminum profiles are perfect for constructing CNC machine frames availing the strength to weight ratios, resistance to corrosion, and ease in assembling. In the details of the construction we are incorporating 3D printed parts for the main framework of the CNC machine for customized and light weight constructions. They suit the aluminum frame and guarantee correct positioning and operation of the frame parts.
To assemble the 3D parts of the CNC machine, I used 12 mm rods and lead screws to connect them. These components ensure linear motion and there is extra support which improves the stability of the machine and it also ensures that the movement is accurate.
Also, we have been employing 5 to 8 couplers connecting the lead screws with the stepper motors. Such arrangement makes it possible for, whenever the motors are on, they translate the lead screws to cause the gantry in the CNC to move along the X, Y and the Z direction.
The 3D simulation of our CNC machine is shown in Figure 3.1

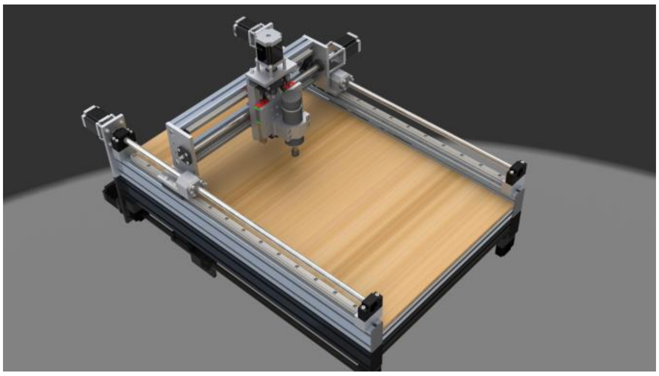

Figure 3.1: Simulation of the CNC Machine frame

In Figure 3.2, the real frame of our CNC machine that we constructed in real life is displayed.

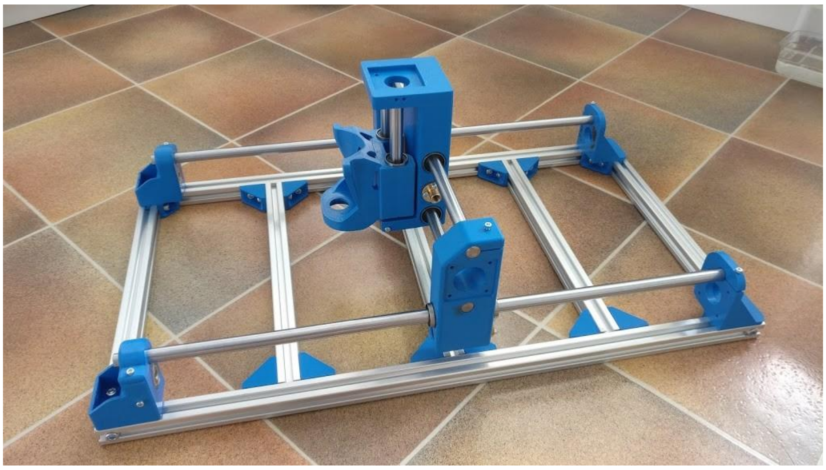

Figure 3.2: our CNC machine

Table 3.1 shows the dimensions of our CNC machine, which is crucial information for the control unit programmer. Knowing the machine's limits is essential to ensure that the borders are not exceeded during operation. This information is necessary for safe and accurate operation of the machine, preventing potential errors and damage.

axis	length(cm)
X Axis Travel	26
Y Axis Travel	50
Z Axis Travel	12
CNC Height	22
CNC Width	40
CNC Length	67

Table 3.1: measurement of CNC

3.4 Electronic Sub System

The electronics system is responsible for generating control signals to the A4988 stepper motor drivers, which in turn control the rotation of the stepper motors. This system guides the motion of the tool path in each direction or axis and consists of several units.

3.4.1 Power Supply

The power supply for the CNC machine is crucial for driving the stepper motors, converting AC voltage to DC voltage and providing the necessary power to all the devices. We are using a 15V power supply to drive the NEMA 17 stepper motors, ensuring they receive the necessary voltage and current for optimal performance.

3.4.2 Stepper Motors

For public recognition, a stepper motor is a brushless motor that works in synchronism, which translates digital signals into mechanical movement. This kind of motor is characterised by its ability to be positioned with high accuracy without the use of feedback hence regarded as an open loop control system. In our project, starting the correct motor movement is a couple of steps and includes mathematical operations and adjustments.

Below are the steps to follow to initiate correct motor movement:

1. Determine the number of steps per revolution based on the motor's angle.
2. Choose an appropriate micro-stepping value, considering the motor driver's specifications.
3. Calculate the number of steps per millimeter for accurate movement.
4. Move the carriage a known distance to test the setup.
5. Measure any error and adjust the settings accordingly.

First of all, with the help of the obtained values, steps per millimeter (steps/mm) are determined. This step may not be necessary when working with geometries that have been previously defined; in such a case, the steps per mill can be obtained from the datasheet. However, in our project, if using recycled parts or variable material , simple arithmetic is required to have a preliminary estimate of the value. This calculation should be made for each axis of the CNC Frame .

While rotating the motor, the displacement in millimeters is computed. After this measurement, there are steps per millimeter calculated according to this measurement.

$$\text{steps per millimeter} = \frac{\text{Steps per revolution}}{\text{mm per revolution} \times \text{micro-stepping fraction}} \tag{3.1}$$

we used a stepper motor with a 200 steps/rev, that is, a stepper motor with 1.8° step. It travels 12.7mm per revolution when operated with 1 micro-stepping.

$$\textbf{Steps per millimeter} = \frac{200 \times 1}{12.7} = 15.748\ \textbf{steps/mm}$$

$$\text{Average Distance Per Turn} = \frac{1}{11}\ \frac{\text{Distance}_1}{\text{Turn}_1} + \frac{\text{Distance}_2}{\text{Turn}_2} + \frac{\text{Distance}_3}{\text{Turn}_3} + \ldots \tag{3.2}$$

To calibrate each axis of our motor, we provided a specific number of steps, starting from 200 steps (representing 1 turn) and incrementing up to 100 turns. For each step count, we measured the distance traveled and calculated the average distance. The results of our calculation are presented in the table 3.2:

Number Of Turn	Distance Travelled (cm)
1	0.127
2	0.3
3	0.41
4	0.55
5	0.68
10	1.25
15	1.8
20	2.5
30	3.8
40	4.35
50	6.55

Table 3.2: distance measurement of CNC

from the result given in the table above we can calculate the average of the distance by centimeter traveled

$$\text{Average Distance Per Turn} = \frac{1}{11}\ \frac{0.127}{1} + \frac{0.3}{2} + \frac{0.41}{3} + \frac{0.55}{4} + \frac{0.68}{5} + \frac{1.25}{10} + \frac{1.8}{15} + \frac{2.5}{20} + \frac{3.8}{30} + \frac{4.35}{40} + \frac{6.55}{50}$$

Calculating each term:

$$\text{Average Distance Per Turn} = \frac{1}{11}(0.127 + 0.15 + 0.13666667 + 0.1375 + 0.136 + 0.125 + 0.12 + 0.125 + 0.12666667 + 0.10875 + 0.131)$$

$$\text{Average Distance Per Turn} = \frac{1}{11} \times 1.372291 \approx 0.1248\ \text{cm}$$

To estimate the errors, we will again divide the distance that the CNC machine is expected to travel by the actual distance measured on each turn. This way it is possible to calculate the error for each step Between these two values, and if necessary adjust the settings.

To measure errors, let's consider the process of drawing a straight line of 5 cm.

1. **Calculate the number of turns needed:**

$$\text{Number of Turns} = \frac{5\ \text{cm}}{0.1248\ \text{cm/turn}} \approx 40.06\ \text{turns}$$

2. **Calculate the number of steps required:** Since each turn corresponds to 200 steps:

$$\text{Number of Steps} = 40.06\ \text{turns} \times 200\ \text{steps/turn} \approx 8012\ \text{steps}$$

3. **Issue the steps to the stepper motor:** The stepper motor is commanded to move 8012 steps.

4. **Measure the actual distance traveled:** After issuing the steps, measure the actual distance the CNC machine traveled.

we found that the actual distance the CNC machine traveled is 5.1 cm

5. **Calculate the error:**

$$\text{Error} = \text{Expected Distance} - \text{Actual Distance} \tag{3.3}$$

knowing that, the actual distance measured is 5.1 cm:

$$\text{Error} = 5\ \text{cm} - 5.01\ \text{cm} = 0.01\ \text{cm}$$

This process ensures that the motor moves the desired distance and helps identify any discrepancies that can be adjusted.

1. **Calculate the error:**

$$\text{Error} = 5\ \text{cm} - 5.1\ \text{cm} = -0.1\ \text{cm}$$

2. **Calculate the absolute value of the error as a percentage:**

$$\text{Percentage Error} = \frac{|\text{Error}|}{\text{Expected Distance}} \times 100 \tag{3.4}$$

$$\text{Percentage Error} = \frac{0.1\ \text{cm}}{5\ \text{cm}} \times 100 = 2\%$$

3.4.3 Digital Controller

As stated in Chapter 2, the aim of our project is to realize a complete CNC machine controlled using an FPGA board. We used the Altera Cyclone IV DE2 board to generate two signals for each axis: the direction signal and the step signal. The direction signal is straightforward to generate; it is set to 1 when the motor rotates clockwise and 0 for counterclockwise rotation. However, generating the step signal is more complex. The FPGA clock runs at 50 MHz, which is too high to directly drive the A4988 stepper motor driver. Therefore, we employed a technique called clock division to reduce the clock frequency to a suitable level for the stepper motor driver. This ensures that the stepper motors receive the appropriate signals for precise control and operation.

3.4.4 Clock Division Technique

Clock division is a method employed for the division of a given clock frequency. This is particularly important because the initial clock frequency may be so high for the application one has in mind. This process involves the use of a counter and involves splitting the input clock frequency by a predefined integer thereby producing a lower output frequency.

In an FPGA, a clock divider can be implemented using an actual counter, that counts the number of clocks being used. All the Cirrus Logic's counter is incremented on the rising edge of the input clock only. The counter when it reaches a specific value will reset and produce pulse, thus giving rise to a new clocking signal with lower frequency. In the Figure 3.3, the simulation illustrates the clock division

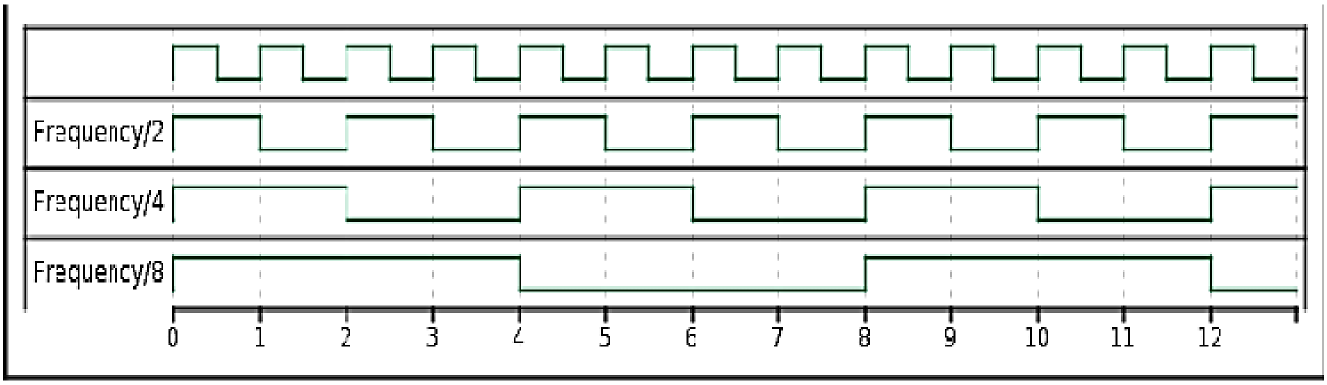

Figure 3.3: Clock Divider technique

by 2, 4, and 8 divisions To Popularize the concepts of computer architecture and organization among the students and other people. The first waveform in the figure depicts the clock input and consists of a sequence of square waves with a frequency of 10 KHz. The second waveform illustrates current clock division by two, meaning frequency is reduced to half, meaning this signal changes state for every two cycles of the clock. On the third figure; it shows the clock waveform divided by 4, providing a reduction of the frequency by changing its state every four actual clock pulses. Also, the fourth wave demonstrates the division of the clock signal by the 8:1 counter which means that the signal states toggle at one-eighth of the clock's frequency. This division process makes it able to reduce the rates of the clock signal which makes it in a position to drive components such as stepper motor driver A4988 at instrumental rates.

3.4.4.1 Example: Dividing 50 MHz to 750 Hz

To divide a 50 MHz clock signal down to approximately 750 Hz, we need to determine the appropriate division factor.

1. **Determine the Division Factor:**

$$\text{Division Factor} = \frac{\text{Input Clock Frequency}}{\text{Desired Output Frequency}} \tag{3.5}$$

$$\text{Division Factor} = \frac{50,000,000\ \text{Hz}}{750\ \text{Hz}} = 66,666.67$$

2. **Choosing the Closest Integer Division Factor:** Since we can't use a fractional division factor, we choose the nearest integer, which is 66,667.

3. **Calculating the Actual Output Frequency:**

$$\text{Actual Output Frequency} = \frac{\text{Input Clock Frequency}}{\text{Division Factor}} \tag{3.6}$$

$$\text{Actual Output Frequency} = \frac{50,000,000\ \text{Hz}}{66,667} \approx 750\ \text{Hz}$$

By using a counter that resets every 66,667 clock cycles, the FPGA can generate a clock signal of approximately 750 Hz from an input clock of 50 MHz.

Now that we have used the frequency divider to get the required frequency of 750 Hz, it is possible to control the stepper motor by using the A4988 stepper motor driver. The A4988 driver is designed to operate at a particular frequency range thus can effectively control stepper motors. To guarantee that the stepper motor adjusts to the required position, we feed it with a 750 Hz step signal. This frequency is ideal for smooth and precise motor movements, which is also appropriate for the use of the A4988 driver. Therefore, with the integration of the frequency divider and the stepper motor driver, the control of the axes of the CNC machine can be well and efficiently implemented.

3.4.5 Stepper Motor Driver Configuration and Operation

Wiring of the Stepper Motor Driver

In our project, the stepper motor driver A4988 is configured to receive the divided clock signals for precise motor control. The wiring setup involves connecting the output of the frequency divider to the step input of the A4988 driver. The direction input of the A4988 is connected to the control signal generated by the FPGA, which determines the rotational direction of the motor. The stepper motor coils are connected to the A4988 motor outputs, ensuring proper phase connections for efficient operation. Power supply connections are made to provide the necessary voltage and current to the driver and motor, ensuring reliable performance. This configuration allows for smooth and accurate control of the stepper motors, essential for the precise movements required in our CNC machine.

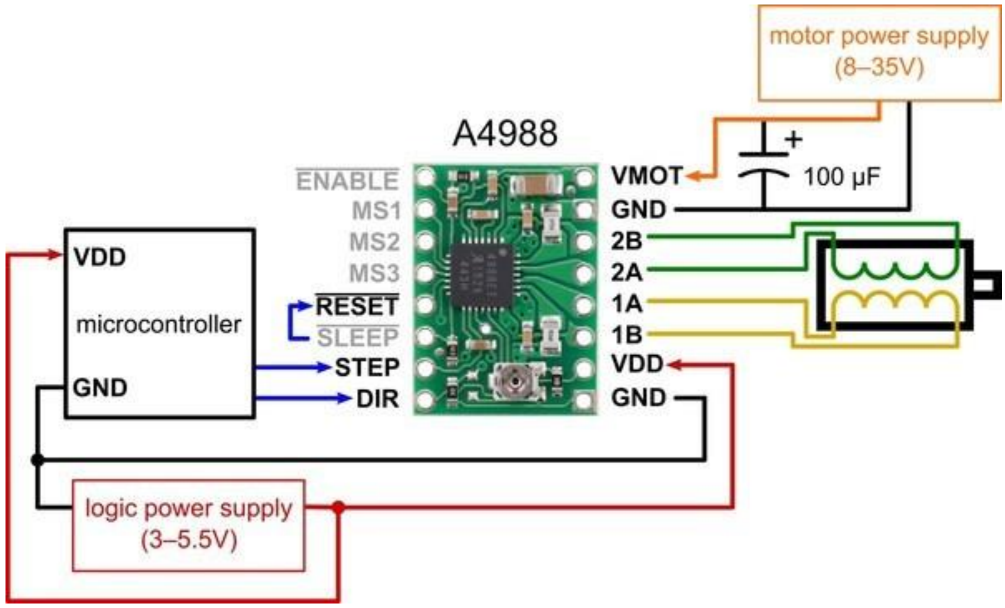

Figure 3.4: Stepper Motor Driver Wiring

3.5 Configuration and Wiring of the A4988 Stepper Motor Driver

The A4988 stepper motor driver is a critical component in our CNC machine project, responsible for controlling the 9stepper motors. The driver has 16 pins, each serving a specific function. To configure the driver without microstepping, we connect the VDD pin to a 5V power supply from the FPGA or an external source and the GND pin to the power supply ground. The motor coils are connected to pins 2A, 2B, 1A, and 1B. The VMOT pin is connected to a 15V power supply for the motors, with the ground connected to the motor power supply ground.

Microstepping is disabled by connecting the MS1, MS2, and MS3 pins to ground. The RESET and SLEEP pins are connected to each other to ensure the driver remains active and awake. The STEP pin receives the step pulses from the FPGA, while the DIR pin receives the direction signal, determining the motor's rotation direction (1 for clockwise and 0 for counterclockwise). Finally, the ENABLE pin is connected to ground to activate the driver. This setup allows the A4988 to control the stepper motors effectively, with the FPGA generating the necessary signals for precise motor movement.

A 100 µF capacitor is used across the VMOT and GND pins to stabilize the power supply voltage and reduce noise and voltage spikes that could potentially damage the driver or disrupt its operation. This capacitor helps in smoothing out the power delivery, ensuring reliable performance.

For our CNC machine, we require four A4988 stepper motor drivers to control the four stepper motors. Each motor, including the two motors on the Y-axis and one each on the X and Z axes, needs its own driver to receive individual control signals and operate independently.

3.5.1 Integration of the SN74LS244N Octal Buffer in CNC Machine Control System

In our realized cnc machine project, the SN74LS244N works as an octal buffer/line driver where it helps to provide buffers to drive multiple loads while exhibiting rail-to-rail output swing. Thirdly, we employ this device to translate signals developed through the FPGA to connect with the stepper motor drivers. The FPGA provides 3. For each of the stepper motors, they provide two 3V logic signals namely; the direction signal and the step signal. However, our stepper motor drivers need 5V logic levels to operate properly, this is why we need LVC circuits.

The first advantage is that the signals going through the SN74LS244N will be less susceptible to noise since the SN74LS244N acts as a buffer that isolates the circuitry from any electrical noise that may disturb the signals. First, the octal buffer actually provide the following conversion of the 3. "The FPGA outputs 3V signals to the motor drivers and makes them compatible to 5V signals." This voltage level shifting is very important in ensuring efficient communication bet9ween the FPGA integrated circuit and the stepper motor drivers integrated circuit. Second, it provides an additional layer of protection, which preserves the input signals by filtering them from the noises and amplifying the signals. This is especially so where the CNC machine is largely electrical and any noise generated can have a bearing on the signals and the motors; their accuracy and controllability.

Further, the 3-state power of the SN74LS244N enables the handling of many signals without interference with correct transmission including the directing of only the right signals to the motor drivers at a given time. The elimination of noise for the stepper motors enhances their control signal, thus resulting in better functionality of Mot-X, Mot-Y, and Mot-Z, which are all stepped motor controls.

Figure 3.5: the SN74LS244N octal buffer

The Figure 3.5 represent the tristate buffer line used in our project. In conclusion, the SN74LS244N octal buffer/line driver is equally a significant component in our CNC machine that enables voltage level shifting, signal conditioning, and removing noise by making sure that the signal is in its correct condition before passing it on to the other components in our circuit, thereby guaranteeing the efficient, safe and accurate movement of the stepper motors.

3.6 Programming And Control Logic

We dive into the Programming and control logic aspects of our CNC machine, focusing on the use of VHDL (VHSIC Hardware Description Language) for FPGA (Field Programmable Gate Array) programming. The precise control afforded by VHDL is essential for the real-time operations required by CNC machines, ensuring accuracy and efficiency in machining processes.

3.6.1 Overview of VHDL

VHDL stands for VHSIC (Very High-Speed Integrated Circuit) Hardware Description Language. It is a powerful language used for describing the behavior and structure of electronic systems, particularly digital circuits.

Using VHDL provides us with lots of advantages over other orthodox methods used to control a typical CNC machine. With its flexibility that allows for precise control over hardware design, and its innate design that supports concurrency which enables simultaneous execution of processes, which is crucial for real-time control.

3.6.2 System Block Diagram

A system block diagram is a fundamental tool used in engineering and design to visually represent the structure and components of a complex system. It provides a high-level overview of the various functional units, their interactions, and the data flow between them, Figure 3.6 shows our entire system block diagram.

By breaking down the system into its core blocks, designers and engineers can better understand the system's architecture, identify potential issues, and communicate the design effectively to stakeholders. This abstraction is crucial in simplifying complex systems, making it easier to manage, troubleshoot, and enhance the design.

In the context of a CNC machine's control system, the system block diagram plays a critical role in illustrating how different modules, such as the clock divider, multiplexer, and shape control modules, interact to achieve precise motor control and shape generation.

Each block in the diagram represents a specific function or process, detailing inputs, outputs, and their connections. This holistic view is essential for ensuring that the entire system operates cohesively, meeting the required performance and reliability standards.

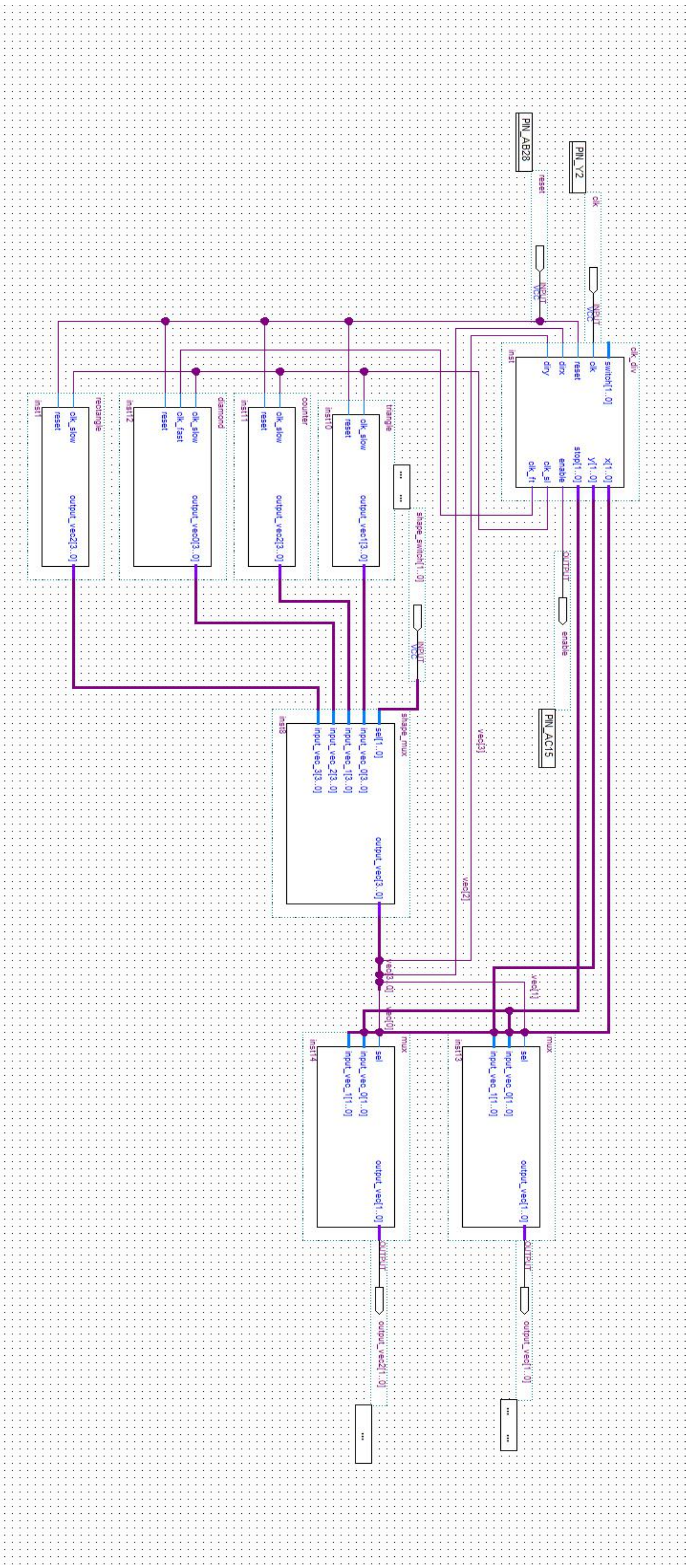

Figure 3.6: First Part of Block Diagram

3.6.3 Exploring System Components

- **Clock Divider:** The clock divider is responsible for generating the required clock signals for different components of the system from the main system clock. This is crucial for synchronizing the operations of all components.
  the

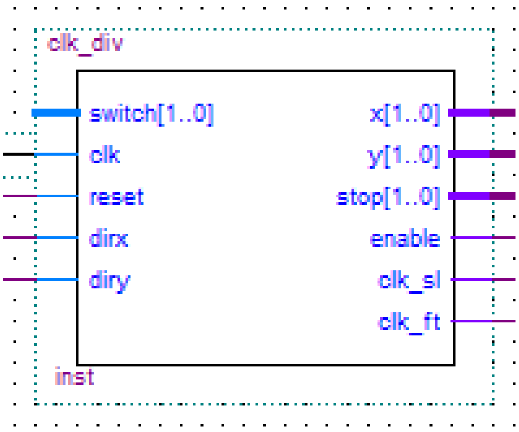

Figure 3.7: clock Divider Block

The clk-div block is a critical component of our CNC machine's control system. It is responsible for converting the 50MHz clock signal from the FPGA into lower-frequency signals suitable for driving the stepper motors and managing the movement of the CNC machine. Here is a detailed description of its inputs, outputs, and functionality: Inputs:

- clk: This is the primary clock input, directly connected to the FPGA's 50MHz clock. It serves as the source clock that needs to be divided down.

- reset: This input is used to reset the clock divider's internal counters and registers, ensuring that the system can start cleanly from a known state.

- dix: This input represents the direction signal for the X-axis motor. It dictates whether the motor moves clockwise or counterclockwise.

- diry: Similar to dix, this input is the direction signal for the Y-axis motor. Outputs:

- clk: This is the primary clock input, directly connected to the FPGA's 50MHz clock. It serves as the source clock that needs to be divided down.

- x[1..0]: This is a 2-bit vector output for the X-axis motor. The two bits represent:
- x[0]: Step signal for the X-axis motor.
- x[1]: Direction signal for the X-axis motor, directly driven by dix.

- y[1..0]: This is a 2-bit vector output for the Y-axis motor. The two bits represent:

- y[0]: Step signal for the Y-axis motor.
- y[1]: Direction signal for the Y-axis motor, directly driven by diry.
- stop[1..0]: These signals are used to stop the X and Y motors, ensuring they do not move when the signal is active. They act as an enable/disable mechanism for the motors.
- clk-sl: This is a clock signal with a frequency of 750Hz, derived from the 50MHz input clock. It is used to control the step rate of the stepper motors, ensuring smooth and precise movements.
- clk-ft: This is another clock signal with a frequency of 1000Hz, also derived from the 50MHz input clock. It serves different timing requirements within the CNC system. The clk-div block in

  our project takes the high-frequency 50MHz clock signal and reduces it to much lower frequencies (750Hz and 1000Hz) suitable for driving the stepper motors. It passes the direction inputs (dix and diry) directly to the X and Y outputs to control the motors' movement direction. The step signals (x[0] and y[0]) are generated based on the divided clock signals, ensuring precise motor movement. The stop signals (stop[0] and stop[1]) can halt the motors immediately, preventing unintended movement. This clock division ensures the stepper motors receive correctly timed signals, crucial for maintaining the precision and reliability of CNC operations.

  The VHDL module for the clock divider takes the high-frequency (50MHz) system clock as input and outputs a lower frequency clock. This is achieved through a counter mechanism that increments with each cycle of the main clock. Specific bits of this counter are used to generate the slower clock signals, ensuring that the system can operate at a manageable speed.

  This block outputs to the multiplexers the stepper motors' step and direction signal

- **Multiplexers:** The multiplexer component selects between different input signals based on control inputs. This allows the system to dynamically switch between different shapes or operational modes, facilitating flexible control over the CNC machine's operations.

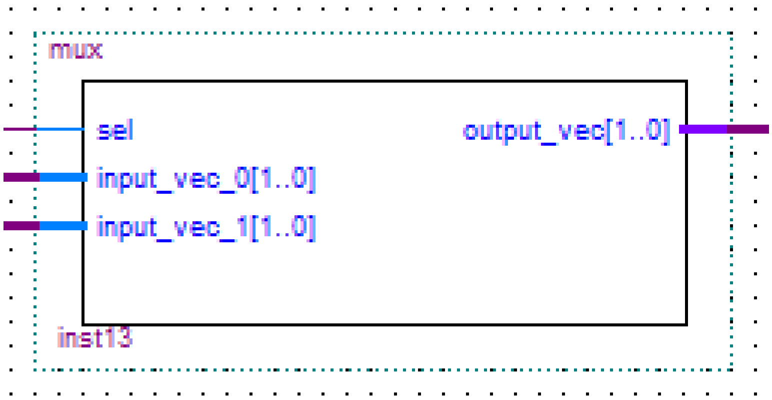

Figure 3.8: Multiplexer Block

The multiplexer block in our project is designed to select between two input vectors and direct the chosen one to the output. It has three inputs: sel, input-vec0[1..0], and input-vec1[1..0]. The sel input determines which of the two input vectors is selected. When sel is set to a specific value, it chooses either input-vec0 or input-vec1 and sends it to the output named output-vect[1..0]. The output is then directed to the motor of each axis, ensuring that the appropriate control signals are routed to the motors based on the selected input vector. This selection mechanism allows for flexible routing of signals, enabling precise control of the CNC machine's movements.

We used two different 2-to-1 vector multiplexer, each for its own stepper motor. It takes the divided clock from the clock divider block and outputs it depending the control signal which is controlled by an output signal from each of the shapes.

- **Shape Selector:** We used a 4-to-1 vector multiplexer that takes the control signals from the following shape modules. its control signal decides which shape to draw using a user input with a switch. The shape-multiplexer block in our project is a pivotal element designed to select

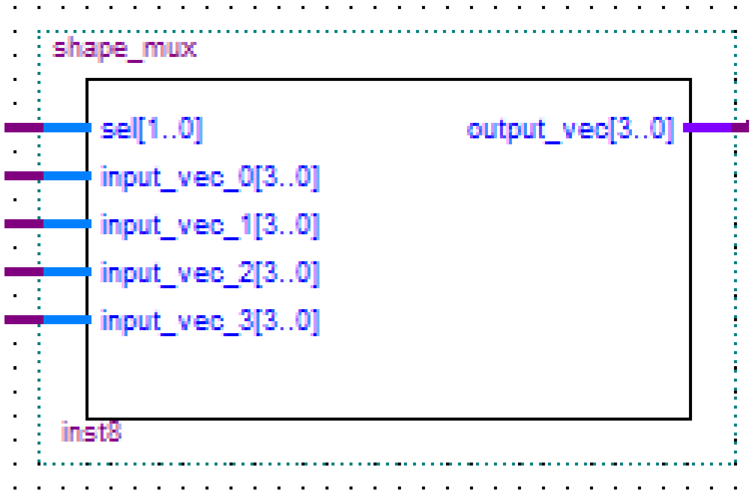

Figure 3.9: Shape-selector block

one of four predefined shapes: he can be triangular, square, diamond, rectangular. It features five inputs: sel[1. .0], input-vector0[3. .0], input-vector1[3. .0], input-vector2[3. .0], and input-vector3[3. .0]. These inputs consist of the selection signals of the desired shapes and the input vector of each shape type, respectively. The shape for which one wants to generate the waveform is selected by the state of switches connected to the sel inputs. When the correct switch setting has been made, the particular input vector chosen in with reference to the selected shape enters the output referred to as output-vector [3. .0].

This output vector includes all the parameters required to define this shape which makes it convenient for additional processes or controls in the CNC machine. As for the significance of the shape-multiplexer block that has been introduced here, we find that the ability to choose and effectively manage the shape of the tool path independently increases the CNC's versatility and utility significantly.

- **Triangle, Square, and Diamond Modules:** Each of these modules is dedicated to generating the specific control signals required to produce the corresponding shapes. They define the precise movements and steps the CNC machine must follow to accurately trace out the desired geometric forms. They all send out 2 output signals "S1" and "S2" which moves the X-axis and Y-axis motors respectively.

  · **Triangle:** The triangle module manages the control logic for producing triangular shapes. It utilizes a slow clock signal and a step counter to control the movements of the CNC machine. The module operates in several phases, each corresponding to a different segment of the triangular path.

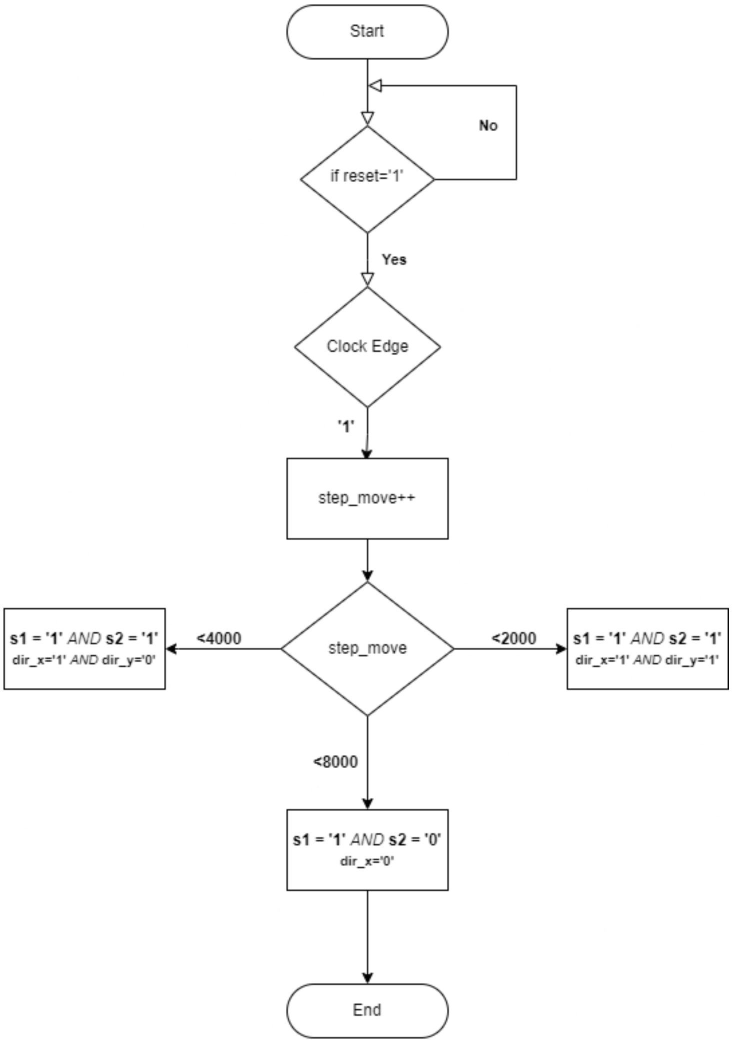

Figure 3.10: Flowchart Of Triangle Control Logic

Initially, the machine moves diagonally by adjusting both X and Y directions. After completing the first segment, it adjusts to move horizontally and then vertically to complete the triangular shape. The directional control signals and step movements are precisely coordinated to ensure the CNC machine accurately traces the triangle.

This is seen in Figure 3.10 in which the step_move is a counter variable that increments according to the rising edge of the divided clock pulse from 0 to 8000 and then loops back. we processes the step_move and made 3 conditions according to its value. if it's less than 2000 both motors move at same speed in one direction drawing a diagonal line upward, when its over 2000 but lower than 4000 it only changes the direction of y-axis to make a diagonal line downward, then the final phase in which only the x-axis motor moves drawing a straight line in the opposite of x-axis finishing the triangle shape.
Figure 3.11 represents the Triangle Shape results produced by our CNC machine.

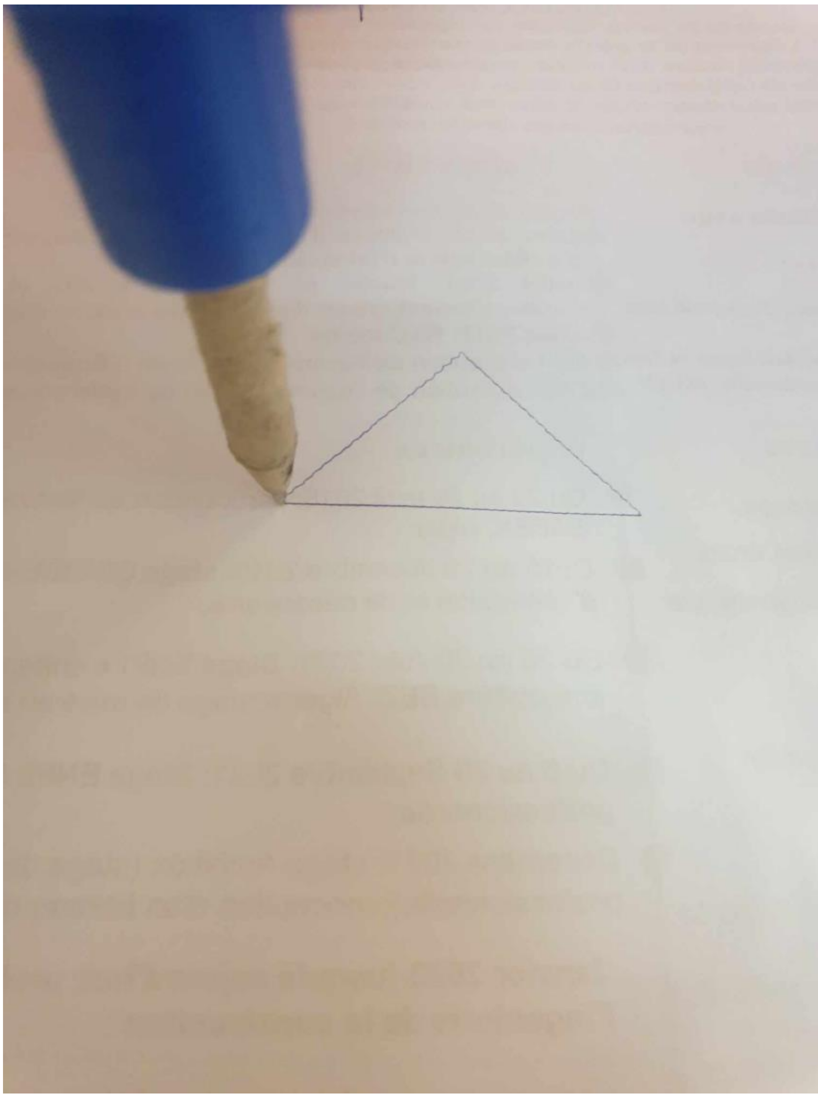

Figure 3.11: Triangle Shape Result Using the CNC

- **Diamond:** The diamond module manages the control logic to create diamond shapes on the CNC machine by using slow and fast clock signals and a step counter.

  It starts by initializing the step counter and setting directional signals for the first diagonal of the diamond. As the step counter increments with each clock cycle, it tracks the machine's progress, adjusting the directional signals at specific thresholds to transition between the diamond's segments. This coordination ensures the machine follows the precise path required to form the diamond shape.

  The module's intricate control logic ensures that each segment is accurately formed, resulting in a precise diamond shape on the work-piece. Figure 3.12 illustrates that there is a counter variable step_move like the triangle block. when it's lower than 2000 both motor move as same speed to draw a diagonal line upward, then at less than 4000 the y-axis direction reverses drawing a diagonal line downward. This process continues to complete the diamond shape.

  Figure 3.13 represents the Diamond Shape results produced by our CNC machine.

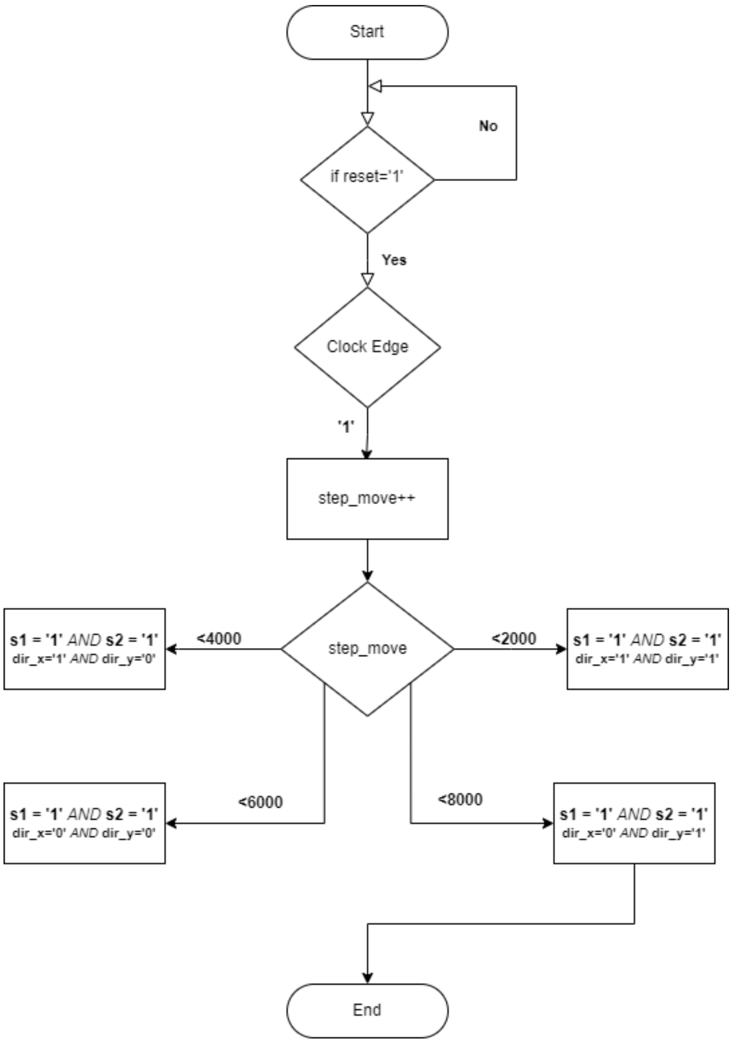

Figure 3.12: Flowchart Of Diamond Control Logic

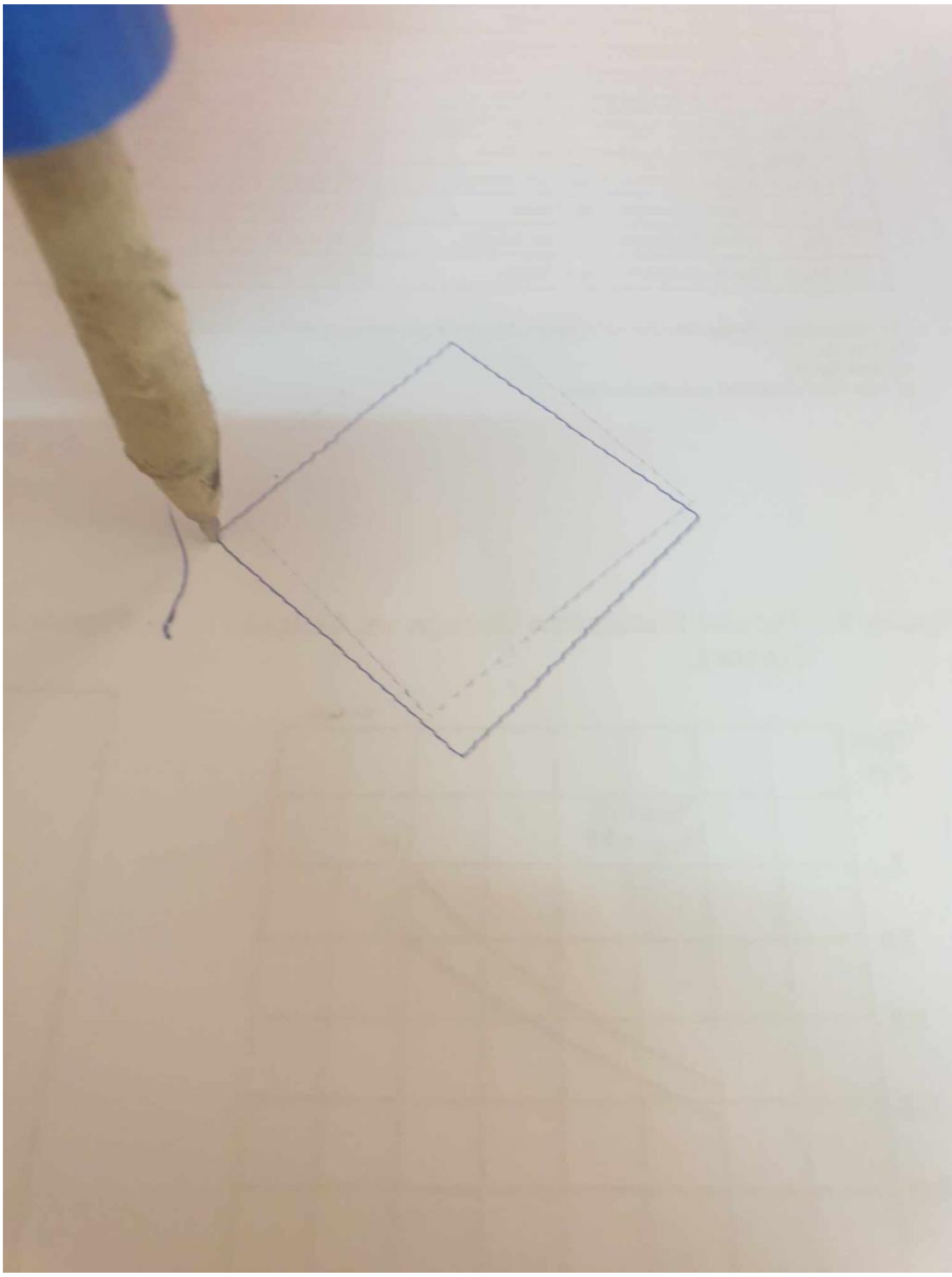

Figure 3.13: Diamond Shape Result Using the CNC

· **Square:** The square module manages the control logic for producing square shapes on the CNC machine. This module utilizes a slow clock signal and a step counter to precisely control the movements of the CNC machine.

Initially, the machine is directed to move along one side of the square by adjusting the X and Y directional signals. After completing the first side, the module changes the direction to trace the next side of the square, and this process repeats for all four sides.

Figure 3.14 shows that if step_move is less than 2000 only x-axis motor moves, then the reverse happens to draw two first lines of a square. Then the process continues to draw the last two lines by reversing the directions of both y and x-axes respectively.

Figure 3.15 represents the Square Shape results produced by our CNC machine.

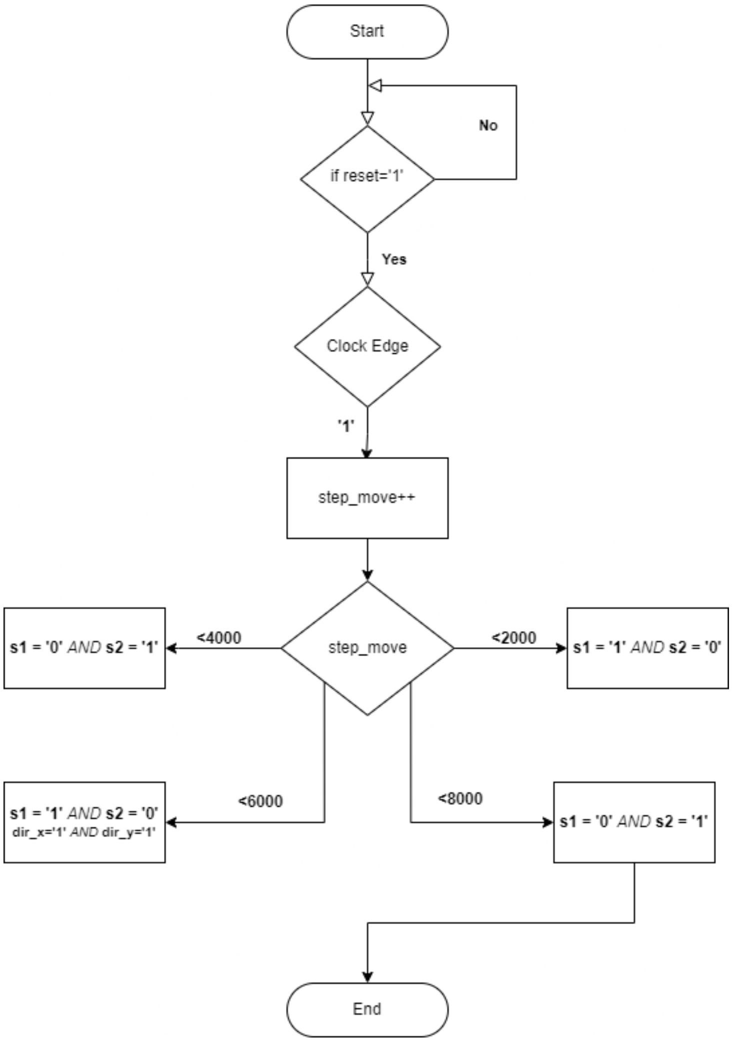

Figure 3.14: Flowchart Of Square Control Logic

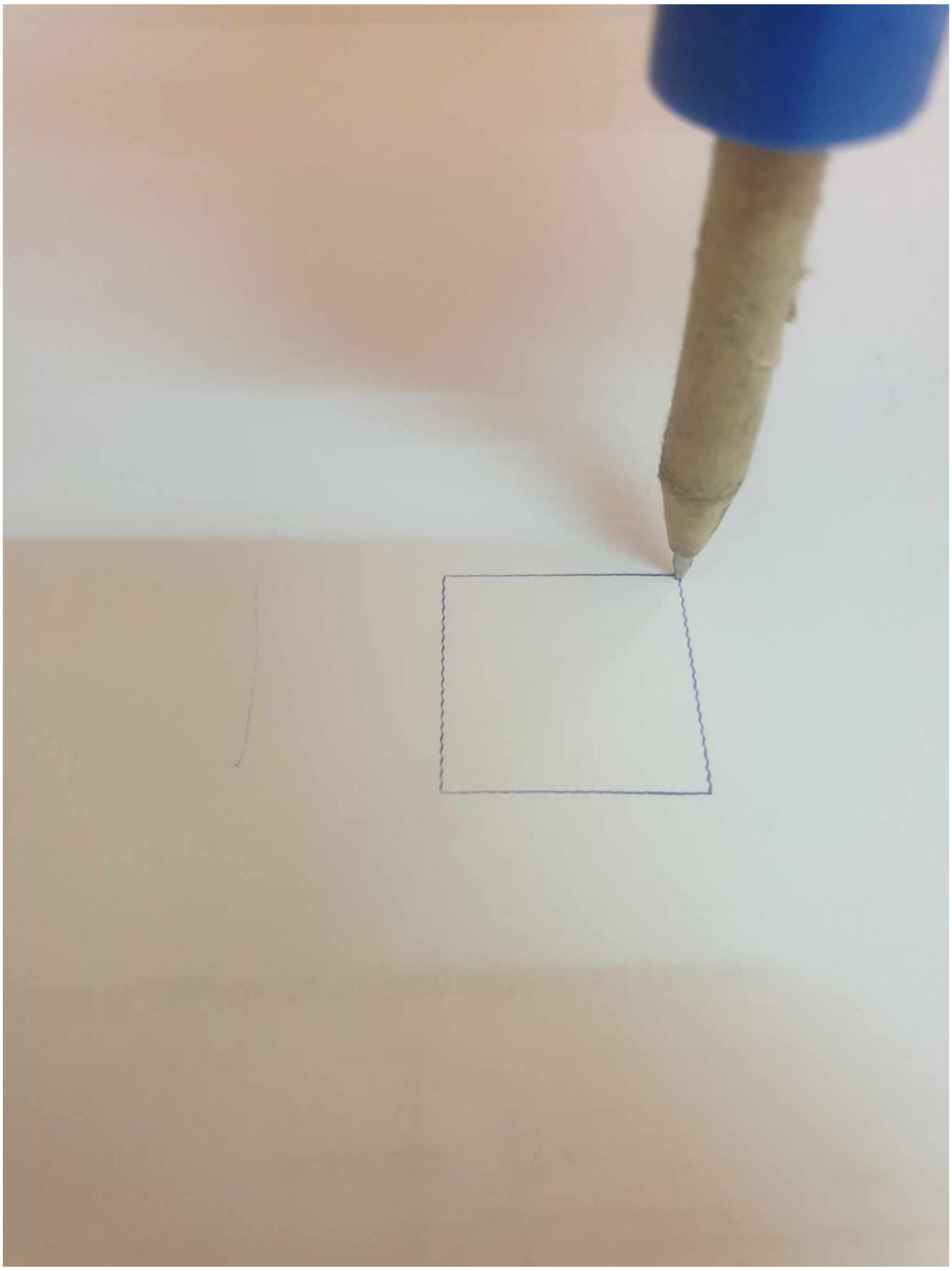

Figure 3.15: Square Shape Result Using the CNC

· **Rectangle:** The square module manages the control logic for producing square shapes on the CNC machine. This module utilizes a slow clock signal and a step counter to precisely control the movements of the CNC machine. It's the same is Logic in the square block except one axis moves for more steps than the other as seen in Figure 3.16

Figure 3.17 represents the Rectangle Shape results produced by our CNC machine.

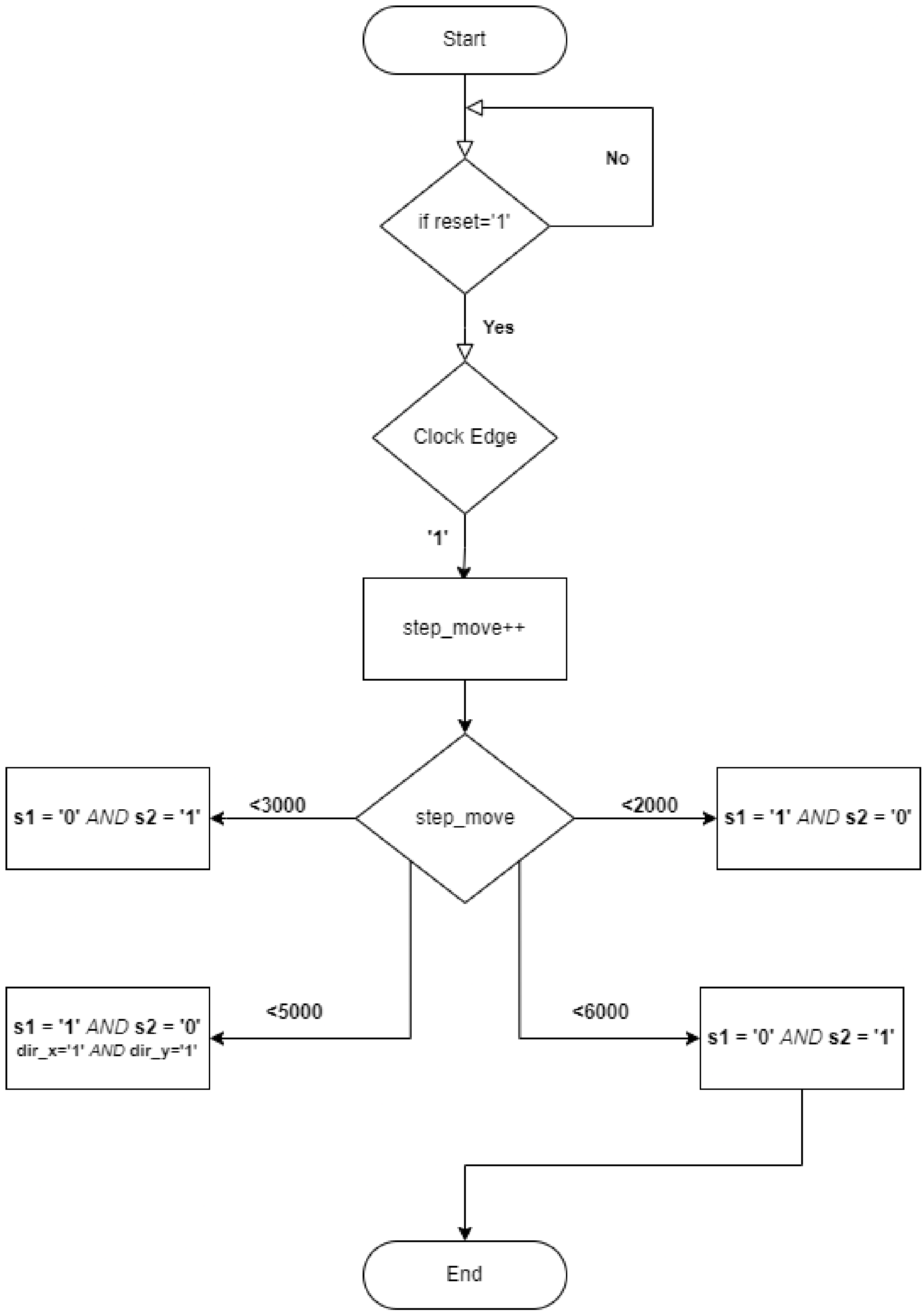

Figure 3.16: Flowchart Of Rectangle Control Logic

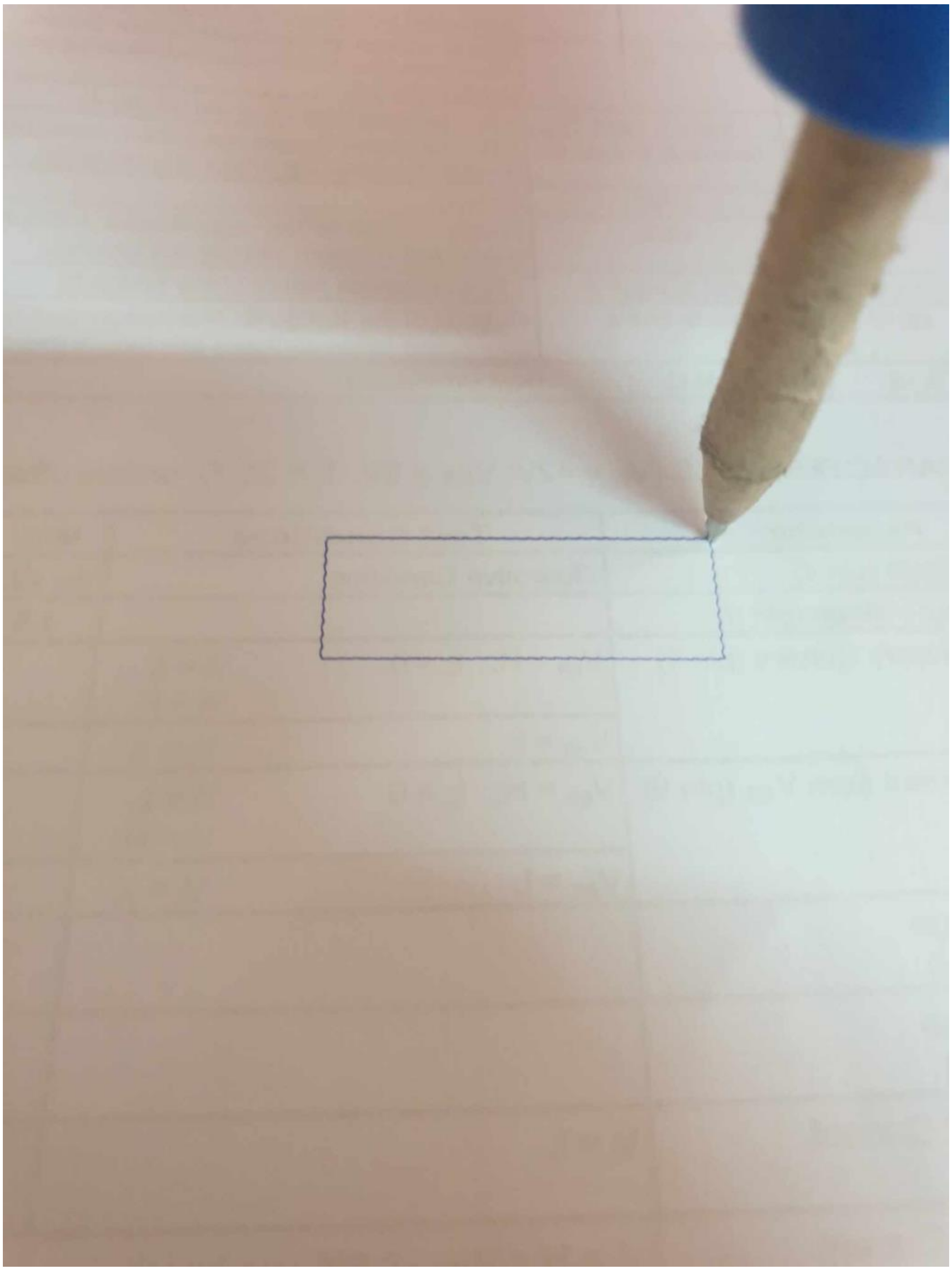

Figure 3.17: Rectangle Shape Result Using the CNC

3.6.4 Overall System

The overall system flowchart provides a comprehensive view of the entire CNC machine's workflow, illustrating how different modules interact to achieve the desired machining tasks. This flowchart helps in understanding the logical flow and decision-making processes involved in the operation of the CNC machine.

As shown in the figure, the system starts with an initial reset check. If the reset signal is active (reset = '1'), the shape switch is activated, determining which shape to select based on the input. The shape switch can choose between Square, Triangle, Diamond, or Rectangle, depending on the input values ("00", "01", "10", or "11" respectively). Each shape selection leads to a specific module designed to handle the operations required for that particular shape.

After the shape is selected, the output is sent to a multiplexer, which consolidates the various shape outputs and directs the appropriate signals to the motor control module. The motor control module then executes the precise movements required to machine the selected shape on the CNC machine.

This structured approach ensures modularity and clarity in the system's design, facilitating easier debugging, maintenance, and potential future enhancements.

The figure 3.18 encapsulates the high-level operational flow of the CNC machine, providing a clear visualization of the interaction between different components and their respective roles in the system.

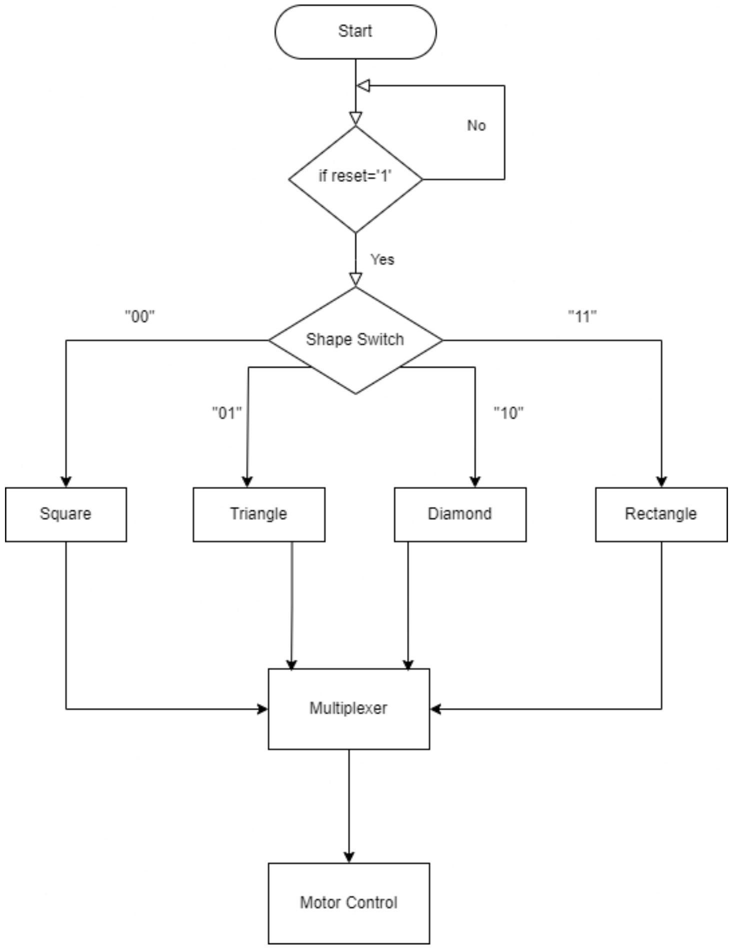

Figure 3.18: Overall high-level operational flow of the CNC machine

Conclusion

In this report, we have explored the intricate design and implementation of a CNC machine, focusing on both the mechanical and electronic subsystems. The integration of precise hardware components with sophisticated control logic underscores the complexity and innovation required to develop a high-functioning CNC machine.

The mechanical subsystem, meticulously described, highlights the selection and configuration of essential hardware components such as motors, CNC structure, and actuators. These components provide the necessary physical movement and precision required for machining tasks. Through careful design and calibration, we ensured that the mechanical system operates with high accuracy and reliability.

The electronic subsystem, driven by VHDL programming, plays a crucial role in controlling and coordinating the operations of the CNC machine. By leveraging the advantages of VHDL, we achieved precise control over hardware design and concurrent execution of processes. This approach facilitated real-time operations, essential for the effective functioning of the CNC machine.

The system's overall functionality was further illustrated through detailed block diagrams and flowcharts. These visual representations provided a comprehensive view of how different modules, such as the clock divider, shape selector, and multiplexer, interact to execute complex machining processes. Each shape module (square, triangle, diamond, and rectangle) was designed to handle specific geometries, showcasing the system's versatility and adaptability.

Throughout the development process, we emphasized modularity, clarity, and precision. The modular design not only facilitated easier debugging and maintenance but also allowed for future enhancements and scalability. The successful integration of mechanical and electronic subsystems demonstrated the feasibility and effectiveness of our design approach.

In conclusion, this report presents a robust framework for the development of CNC machines, combining precise hardware engineering with advanced control logic. The insights gained from this project helps in the broader field of CNC technology, offering potential pathways for further research and innovation. As CNC machines continue to evolve, the methodologies and principles outlined in this report will serve as a foundational reference for future advancements.

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