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Design and Fabrication of CNC Milling Machine

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

---

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September 2023

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ABSTRACT

This thesis report focuses on the development of a miniature CNC milling machine with high precision capabilities for manufacturing complex geometries. The aim is to create a machine that meets ISO standards and produces highly accurate machined parts that enhance machine performance and lifespan. Unlike existing CNC machines, this machine employs AI and sensors, such as ultrasonic sensors, to ensure precise component movement. The machine can manufacture parts like drone wings, which have better strength than those manufactured by casting. Additionally, the unique assembly structure of the CNC milling machine minimizes vibrations during machining. The fabricated machine is also portable and can be easily carried by two or three people. By loading the G and M code in the machine, the desired geometry can be achieved with almost negligible deviation from the CAD model due to the machine's superior accuracy. Overall, this project provides a solution for highly accurate and portable manufacturing of complex geometries in miniature CNC machines.

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We would like to express our sincere gratitude to everyone who supported us in completing this thesis report. First and foremost, we extend our heartfelt thanks to our supervisor, Dr. Salman, for his unwavering guidance, support, and encouragement throughout the project. Their expertise, insights, and constructive feedback have been invaluable in shaping our research and refining our analysis.

We would also like to thank the faculty members of the SMME at NUST for their valuable inputs and feedback during the course of our study. Their intellectual rigor and insightful critiques have helped us to deepen our understanding of the subject matter.

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CHAPTER 1: INTRODUCTION

In the field of manufacturing and fabrication, the pursuit of improved precision and efficiency has driven significant advancements in machinery and technology. Among these innovations, Computer Numerical Control (CNC) machines have emerged as essential tools, revolutionizing the process of shaping raw materials into intricately designed components. This project aims to design and fabricate a 3-axis milling CNC machine capable of precise and automated milling operations on various materials. Additionally, the design incorporates a modular approach, allowing for future expansion to a 5-axis milling machine.

Milling Machine is a multitasking machine that removes material from the workpiece by feeding the work past a rotating cutting tool. Milling Machines add more precision and accuracy to finished products furthermore the process is faster and more reliable. The development of the CNC system added to machines to reduce human interaction with products that greatly reduce human errors like dimensional tolerances, precision, accuracy, etc.

The design process of this CNC machine involves the creation of a robust mechanical structure, careful selection and integration of suitable electrical and electronic components, and the implementation of efficient control software. The completed 3-axis CNC machine will enable users to execute complex milling tasks with high accuracy and efficiency. Moreover, the modular design approach ensures the potential for expanding the machine's capabilities to a 5-axis system.

By incorporating the possibility for a 5-axis configuration, our CNC milling machine goes beyond traditional milling capabilities. This feature unlocks new dimensions in manufacturing, allowing for the creation of intricate geometries and expanding the range of possible machining operations. The addition of two extra axes to the existing X-axis assembly provides operators with enhanced versatility, empowering them to tackle more demanding tasks and explore innovative possibilities.

In traditional design, philosophy machine tools are designed with multitasking and the highest precision. A single machine and tools are used for different processes like drilling, milling, and turning. However, due to the dramatic increase in demand for products, general-purpose machines and tools are not efficient, either in terms of cost or production time. In modern times industry required a single-tasking machine with specific purpose tools which are not only cost-effective but also time efficient. The volume of machines and tools also has a great impact on the machining process. To machine small objects with a volume below 106mm large machine and tools does not give good precision and accuracy. [1] For constant relative accuracy with good resolution and precision, while remaining cost-effective and time efficient small-scale machines are made. These small-scale machines not only give high accuracy at a high rate but are also used to make complex parts.

Utilizing a smaller machine for small-sized objects offers numerous advantages. Firstly, a smaller machine size helps save space, making it more suitable for compact environments. Additionally, operating a smaller machine requires less energy consumption, resulting in reduced energy costs. The manufacturing process also benefits from this size reduction, as it necessitates fewer materials and components, leading to significant cost savings.

Furthermore, the reduced weight of the moving components in a smaller machine contributes to lower levels of vibration, noise, and environmental pollution during operation. The compact and lighter design of the machine enhances its portability, allowing for easier transportation and flexibility in the layout of the manufacturing plant. Moreover, the smaller machine size can lead to improved productivity and faster manufacturing speeds, as it enables faster operation and more efficient production processes.

Cost-effectiveness and precision remain key considerations in the design process. Our approach balances affordability with outstanding accuracy, reliability, and repeatability. This CNC machine aims to provide small businesses, entrepreneurs, and hobbyists access to advanced manufacturing capabilities, enabling ground breaking advancements across various industries.

Safety is a top priority throughout the development of this CNC milling machine. Incorporating fail-safe mechanisms, including limit switches, ensures that the machine cannot reach extreme positions, mitigating potential risks to both the equipment and the operator. By prioritizing safety, we deliver a solution that seamlessly integrates efficiency, precision, and peace of mind.

By designing and fabricating this 3-axis milling CNC machine with potential for expansion to a 5-axis system, we contribute to the advancement of CNC technology and its applications in manufacturing industries. The machine enables precise and automated milling operations while offering the flexibility to evolve with the ever-changing needs of the industry. This project paves the way for a future where precision engineering, automation, and adaptability combine to redefine the boundaries of what is possible.

In conclusion, this project aims to design and fabricate a 3-axis milling CNC machine capable of precise and automated operations, with the potential for expansion to a 5-axis system. Through careful mechanical design, integration of suitable components, and implementation of control software, this machine empowers users to execute complex milling tasks with high accuracy and efficiency. By envisioning future advancements, this project contributes to the progress of manufacturing industries, unlocking new dimensions in precision engineering and manufacturing excellence.

1.1 The Motivation for the Project

CNC Milling machines are widely used in manufacturing industries. A range of manufacturing processes is done by milling machines. Pakistan's industries are mostly small and medium-scale industries and very few large-scale industries. Large-scale industries have a lot of capital and they purchase these machines from countries like China, Taiwan, and the United Kingdom. Pakistan is one of the main importers of CNC machines with 2700 machines till December 2022. [1]

It shows industries in Pakistan have to spend a lot of money for buying these machines from other countries other than that they have to pay extra delivery charges as well as state taxes which also increase the price hugely. Other than that buying CNC machines from other countries also comes with certain risk factors for example the risk of damage during delivery. There are also some other risks and worries like the non-availability of official help from companies' stores from where they are purchasing these machines.

For medium-scale industries, it becomes more challenging due to their limited budgets and other factors so sometimes they compromise and have to turn towards lower quality or high-risk factors. So, they use Milling and other manual machines that require labor to do all work, and their precision and accuracy are also hugely affected by human errors. Due to this machining parts produced by medium-scale industries usually do not have relatively constant dimensional tolerances and accuracy.

On the other hand, small scale industries very few have these, local market survey of Pakistan shows that more than 90% of small-scale industries do not use CNC machines rather they use manual ones. Due to this, local vendors have to compromise or import important parts from other countries.

The needs and importance of CNC Machines for our industries cannot be overlooked. For our industries to compete with international industries in terms of manufacturing we need the finished product to have relatively constant accuracy and precision. The time it takes for a single product to be manufactured is very important, every manufacturing industry in the world is working on reducing this time as much as possible to increase efficiency. Also, the lesser the interaction between manufacturing products and humans lesser will be the human errors in finished products. By considering all factors the best machines for manufacturing our CNC Machines.

In Pakistan, our industries have a lot of Manual Milling machines but the availability of CNC Milling Machines is scarce. For industries to grow CNC Machines' constant availability is very important. In Pakistan, we have a lot of market space for CNC machines manufacturing. Almost no one in Pakistan is currently producing CNC Machines. Apart from Pakistan, the global **computer numerical control (CNC) machine market size** was estimated at **USD 96.4 billion in 2021** and it is expected to hit around **USD 153.8 billion by 2030**, poised to grow at a compound annual growth rate **(CAGR) of 5.33% from 2022 to 2030**.

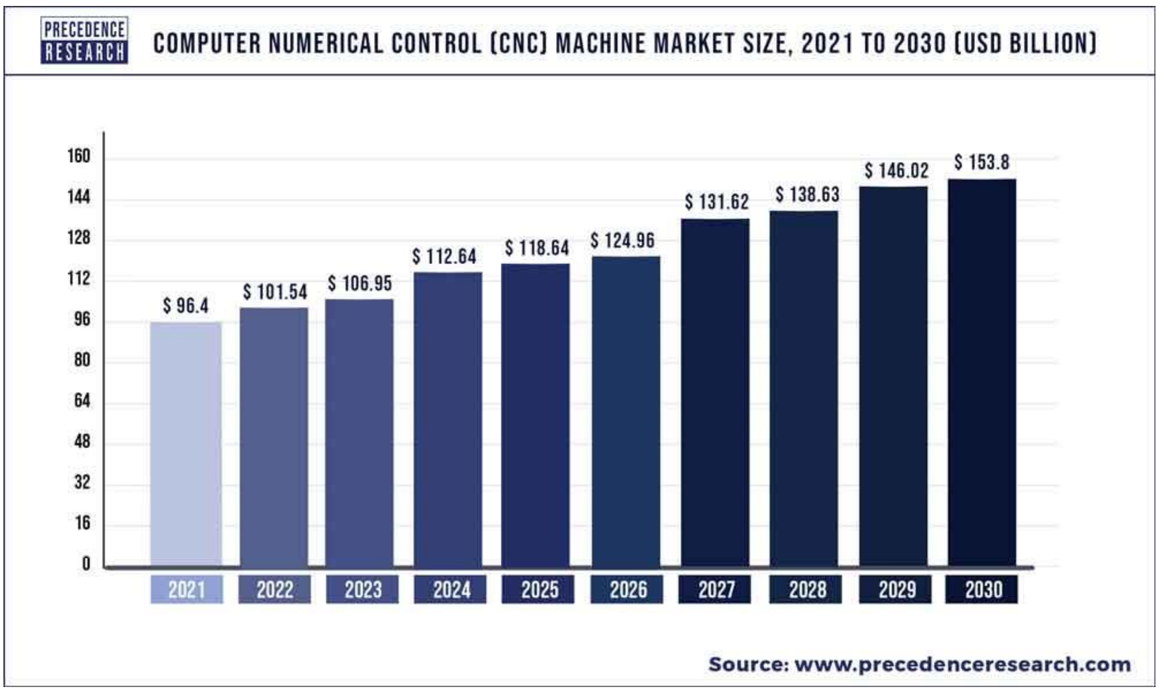

Figure 1.1 shows the yearly growth of CNC Machine Market

1.2 Problem Statement

Designing, analyzing, and fabricating of scale-down 3-axis CNC Milling Machine with high precision and relatively constant accuracy which will be cost-effective as compared to other scale-down machines available.

1.3 Objective of Project

The objective of this project is to design and fabricate a 3-axis CNC milling machine that can be used to create complex parts and components with precision. The machine will be capable of machining various materials, including metals, plastics, and composites. The components created by CNC Milling Machine should be relatively precise and constantly accurate. Apart from increasing precision accuracy and time efficiency, our other main purpose is to reduce the price as much as possible.

CHAPTER 2: LITERATURE REVIEW

Contrary to popular belief, the origins of CNC machining did not involve computerized processes. The first CNC machine is credited to James Parsons in 1949, who used a punched card with data from an Air Force Research Project on helicopter blades and aircraft skin to operate a Swiss jig borer. This led to the production of numerous helicopter blades and aircraft skins. Although it was a groundbreaking achievement, it was only recently computerized. Parsons received recognition for his work with the Joseph Maria Jacquard Memorial Awards, according to the established history of CNC machining.

We embarked on a trip to investigate the background of CNC. We took the time to do the necessary research because we believe the complete narrative hasn't been shared and it should be. What we discovered was a fascinating account of how humans have sought greater precision and efficiency through equipment. A machine tool is fundamentally different from a hand tool or, really, any tool before machine tooling was established, as the toolpath is guided by the machine rather than by direct, freehand human supervision.

The development of CNC machines was made possible by several innovations. Here, we examine four fundamentals: early machine tools, punched cards, servomotors, and the Automatically Programmed Tool (APT) programming language.

First, a shout-out to what is generally regarded as the first machine tool: The answer to precisely boring cylinders for steam engines was found in 1775 with John Wilkinson's boring machine. James Watt is credited with developing the steam engine that propelled the Second Industrial Revolution in England, but until Wilkinson created his engine cylinder boring

machine based on the concept of his first cannon-boring machine, Watt struggled to achieve consistent precision in his steam engine cylinders. This is shown in fig. [2.1].

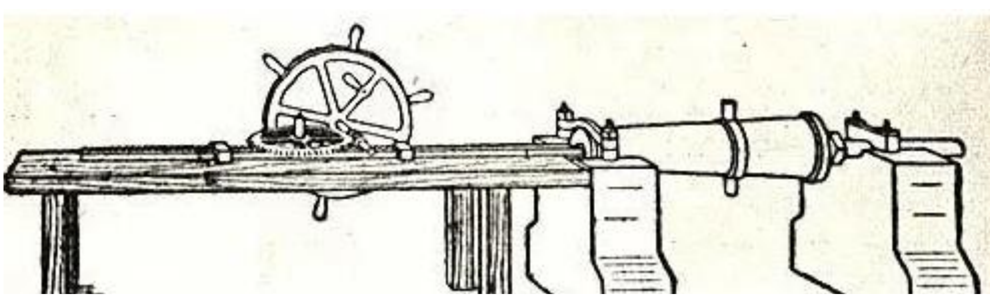

Figure 2.1: Early times CNC machines

Over the second half of the 1800s, punched cards were developed and found usage in a variety of applications, including telegraphy and self-playing pianos. Early cards dictated mechanical control, but American inventor Herman Hollerith invented the first electromechanical punched card tabulator, which changed the rules. While he was employed by the US Census Bureau, his system was patented in 1889. This is shown in fig. [2.2].

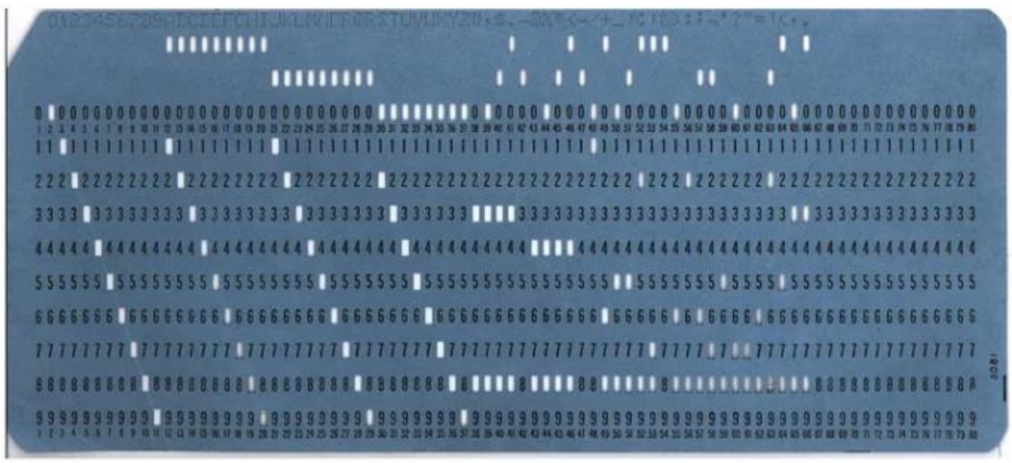

Figure 2.2: Punched Card

A servomechanism is a mechanical system that automatically adjusts the performance of a machine or mechanism based on feedback that detects errors. In some circumstances, the servo enables control of substantial amounts of power by an apparatus with much lower power. A servomechanism consists of a device that receives orders, a device that is controlled, a device that amplifies error signals, a device that detects errors, and a device that corrects the faults (the servomotor). Most frequently made of electrical, pneumatic, or hydraulic components, servos are used to regulate variables like position and speed. This is shown in fig. [2.3].

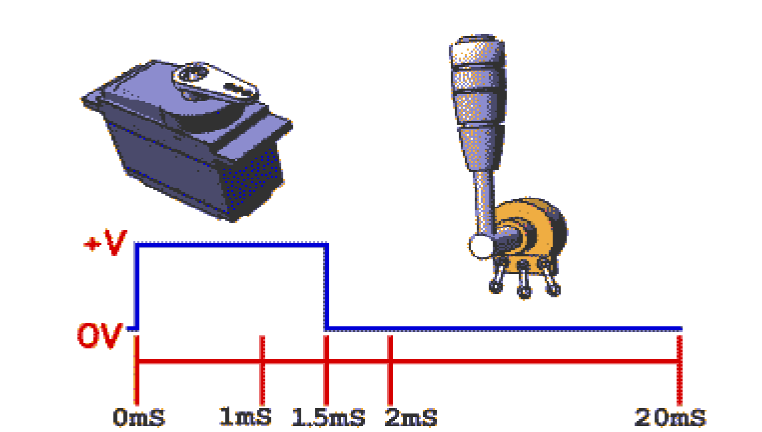

Figure 2.3: Servomechanism used in CNC

The origin of numerical control (NC) technology and NC machine tools predates computer-controlled machines. Although historical accounts may vary, the earliest NC machine tools were developed to address specific production challenges faced by the military and evolved from the punch card system.

Numerical control involves automating tool control for machining operations using programmable logic, utilizing data in the form of letters, numbers, symbols, words, or a combination thereof. Prior to its invention, machining tools were operated manually by human operators.

Computer numerical control (CNC) is a method where precisely coded instructions are communicated to a microprocessor in the control system of a cutting tool, aiming to enhance precision and consistency. Nowadays, when the term "CNC" is used, it commonly refers to a milling machine connected to a computer. However, technically, it can refer to any computer-controlled device.

The foundational elements of earlier control systems still form the basis for the highly automated motion control systems employed by manufacturers today. These systems require a command function (activated by means such as a cam follower, encoder, digital or analog system, or a lever), a motion or drive system (such as a motor, cylinder, valve, or clutch), and a feedback system. In earlier NC machines, a control lever would be mounted on a cam, and the machine would be operated by a counterclockwise-spinning motor. However, if the feedback wire were to break, there was no way to stop the flow of fluid.

The first CNC milling machine, the Cincinnati Milacron Hydrotel, was developed in 1952 by Richard Kegg and MIT. Richard Kegg later submitted a patent application for the Motor Controlled Apparatus for Positioning Machine Tool. The invention of computer-aided design (CAD) and computer-aided manufacturing (CAM) in 1972 further propelled the advancement of CNC machining. The integration of CAD and CAM led to significant progress in CNC machining, although they were not yet considered standard steps in the production process.

New CNC systems not only need to keep pace with advancements in machine tool technology but also meet the operational and programming requirements of manufacturing processes. With complex machine movements, particularly in genuine five-axis machining, additional CNC tasks are necessary. The increasing complexity of multi-axis machining and rising quick traverse and machining rates make it more challenging for machine operators to anticipate axis movements within the machining envelope. Consequently, collision prevention technology has become essential.

Thermal instability within a machine can result in quality issues in multi-axis machining. Temperature factors affect machine accuracy, which, in turn, affects part accuracy. Kinematic compensating techniques in the control system can mitigate these inaccuracies. A new function involving a 3-D touch trigger probe has been developed to measure multiple rotating axis points on a calibration sphere with known and precise dimensions. This helps address thermal instability concerns and enhance overall accuracy.

Shorter block processing, which can only be achieved through improved joint engineering connections between the control builder and machine builder, allows CNCs to keep up with the trend towards greater feed rates and more accurate cutting paths. Moreover, machining time and errors are decreased using cutting-edge contour filters, fresh algorithms, and cutting-edge computer technology. Applying simulation, verification, and optimization software, a development in CNC machinery technology helps businesses save time and money by lowering scrap and minimizing damage to machining centers.

These software packages are offered by several organizations, some of which have cutting-edge and distinctive features while others generally give standard fundamental functions. These software programs enable the machining of new parts to be simulated, tool paths to be verified to prevent crashes and collisions, and production to be optimized. By enabling the identification of disparities through measurement and analysis, they also aid in removing any surprises.

There have been significant advancements in machining center control software, but smarter software necessitates smarter hardware. More sensing devices and probes required to be utilized on the workpieces, the tools, and the machining center itself in order to execute adaptive control and condition monitoring successfully.

2.1 Role of CNC milling in Industry:

CNC milling machines play a critical function in the production enterprise, supplying several advantages and riding advancements in precision engineering. Here are a few key roles and contributions of CNC milling machines:

Automation and Efficiency: CNC milling machines automate the milling procedure, reducing the want for guide intervention and human blunders. They can function constantly, 24/7, enhancing production efficiency and decreasing labor prices. With the potential to execute complex milling obligations with high pace and accuracy, CNC machines extensively growth manufacturing productiveness.

Precision and Accuracy: CNC milling machines offer awesome precision and accuracy in machining operations. The computer-controlled movements remove inconsistencies and versions because of human factors, ensuring constant quality and dimensional accuracy inside the finished merchandise. This stage of precision allows for the production of tricky geometries and tight tolerances which can be challenging to reap manually.

Versatility and Flexibility: CNC milling machines provide versatility in phrases of the substances they are able to paintings with and the range of machining operations they are able to carry out. They can mill a huge kind of substances, inclusive of metals, plastics, composites, and extra. Additionally, they could execute various milling responsibilities, such as contouring, slotting, drilling, and threading, enabling manufacturers to supply complex parts and components for numerous industries.

Reproducibility and Consistency: CNC milling machines excel at producing steady and repeatable effects. Once a machining program is evolved and optimized, it may be replicated across multiple workpieces with the equal stage of accuracy and precision. This reproducibility ensures uniformity inside the synthetic parts, facilitating assembly and interchangeability in large systems or products.

Time and Cost Savings: CNC milling machines provide widespread time and price financial savings within the manufacturing manner. With their excessive-pace operations and automation talents, they can entire complicated milling duties in a fraction of the time it might take using conventional guide techniques. Additionally, the reduction in human errors and scrap prices minimizes fabric wastage, optimizing manufacturing charges.

Design Flexibility and Innovation: CNC milling machines permit designers and engineers to push the limits of layout and innovation. The precise control over device actions allows for the creation of complex and complex shapes, contours, and surface finishes. This layout flexibility encourages experimentation and the improvement of revolutionary products that have been formerly challenging or not possible to manufacture.

Integration with CAD/CAM Systems: CNC milling machines seamlessly combine with Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software systems. This integration permits for efficient programming and simulation of machining operations, optimizing tool paths and minimizing mistakes. The virtual workflow from layout to production streamlines the producing process and facilitates layout adjustments and iterations.

In summary, CNC milling machines have revolutionized the producing industry by supplying automation, precision, versatility, and fee-effectiveness. They allow manufacturers to produce extraordinary, complex parts with efficiency, consistency, and innovation. With their necessary position within the production environment, CNC milling machines keep to force improvements and shape diverse industries, from aerospace and automobile to electronics and scientific devices.

2.2 Principle in CNC milling:

CNC machining, or Computer Numerical Control machining, differs from traditional machining methods in numerous key concepts. Here are the principles that set CNC machining apart:

Automation and Control: In CNC machining, the entire machining system is computerized and managed with the aid of computer structures. CNC machines are programmed with a fixed of instructions that dictate the device movements, reducing parameters, and different machining operations. This automation gets rid of the want for guide manipulate and intervention, decreasing human mistakes and making sure steady and specific results.

Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM): CNC machining integrates CAD and CAM software systems. CAD software is used to create a virtual 3D version of the component to be machined, at the same time as CAM software program generates the tool paths and machining commands based totally at the CAD model. This digital workflow streamlines the producing procedure, permits for complicated geometries, and helps layout modifications and optimizations.

Precision and Accuracy: CNC machining offers high precision and accuracy as compared to standard machining methods. The laptop-controlled moves of CNC machines allow specific positioning of the reducing device and regular repeatability. This outcomes in tight tolerances, uniformity, and improved standard component first-class.

Versatility and Flexibility: CNC machines are exceedingly flexible and can carry out a huge variety of machining operations. They can mill, drill, bore, tap, turn, and carry out diverse other operations, all with the identical machine. This flexibility lets in manufacturers to provide complicated parts and components for various industries without the want for multiple specialized machines.

Multi-Axis Machining: CNC machines often have multiple axes of motion, inclusive of three-axis (X, Y, Z) or maybe five-axis configurations. These additional axes permit machining operations from a couple of angles and orientations, facilitating the production of complex shapes, contours, and undercuts which are challenging with conventional machines.

Programmability and Reproducibility: CNC machines are pretty programmable, which means that machining programs can be created, saved, and reused for destiny production runs. Once a software is advanced and optimized, it is able to be replicated across multiple workpieces with regular consequences. This reproducibility improves performance, reduces setup times, and ensures uniformity in the manufactured elements.

Real-time Monitoring and Feedback: CNC machines regularly contain sensors and comments mechanisms that permit for real-time monitoring of the machining manner. These sensors can degree cutting forces, tool wear, temperature, and different parameters, supplying treasured statistics for system optimization, tool existence control, and exceptional manipulate.

Reduced Manual Labor: CNC machining reduces the reliance on guide hard work as compared to traditional machining techniques. Once the CNC system is installation and programmed, it could function autonomously, requiring minimum human intervention. This reduces hard work charges, will increase productivity, and lets in operators to focus on other responsibilities including programming, excellent control, and technique development.

Overall, CNC machining standards revolve around automation, precision, flexibility, and efficiency. The integration of advanced software program structures, automation, and manipulate mechanisms allows manufacturers to attain higher accuracy, produce complex elements, and streamline the producing technique compared to conventional machining methods.

2.3 Capabilities of CNC milling:

High Precision Machining: CNC milling machines provide terrific precision in machining operations. With their laptop-managed movements and correct positioning, they are able to gain tight tolerances and convey components with high dimensional accuracy.

Complex Geometries: CNC milling machines excel at machining complicated geometries, inclusive of complex shapes, contours, undercuts, and patterns. The multi-axis configurations allow for machining from numerous angles, enabling the introduction of particularly problematic and unique elements.

Versatile Material Compatibility: CNC milling machines can work with a wide range of materials, which include metals (consisting of aluminum, metal, titanium), plastics, composites, and greater. This versatility makes them suitable for various industries, from aerospace and automobile to electronics and clinical.

Multi-Axis Machining: Many CNC milling machines have multiple axes of movement, inclusive of 3-axis (X, Y, Z) or five-axis configurations. The additional axes enable machining operations from one-of-a-kind angles, making an allowance for complex and multi-sided machining in a single setup.

Efficient Batch Production: CNC milling machines are best for batch production because of their high repeatability and software-based totally operation. Once a machining application is developed and optimized, it could be replicated throughout a couple of workpieces, making sure steady first-class and lowering setup times.

Rapid Prototyping: CNC milling machines play a important role in rapid prototyping. They allow designers and engineers to quickly rework virtual CAD fashions into bodily prototypes, permitting iterative layout strategies, quicker product improvement cycles, and checking out of design concepts.

Customization and Small-Scale Production: CNC milling machines permit customization and small-scale manufacturing. With their capacity to device complicated info and produce parts on call for, they cater to particular consumer necessities, niche markets, and specialized packages.

Integration with CAD/CAM Software: CNC milling machines seamlessly combine with Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software systems. This integration allows green programming, simulation of machining operations, and optimization of device paths for stepped forward productivity and pleasant.

High-Speed Machining: CNC milling machines can function at excessive speeds, ensuing in quicker machining instances and extended productiveness. This functionality is beneficial for industries with high production demands and time-touchy tasks.

Quality Control and Inspection: CNC milling machines regularly include sensors and dimension tools for actual-time best manage and inspection. These sensors can screen cutting forces, device wear, and floor end, ensuring constant first-class at some point of the machining procedure.

Automation and Unattended Operation: CNC milling machines provide automation features, bearing in mind unattended operation. Once the system is installation and programmed, it can run autonomously, freeing up operators for other obligations and maximizing productiveness.

Scalability and Expansion: CNC milling machines frequently have a modular design, taking into account destiny enhancements and expansions. They may be adapted to accommodate extra axes, tool changers, and add-ons, enabling the system to adapt and meet converting manufacturing necessities.

In end, CNC milling machines own a wide range of abilties, including excessive precision machining, versatility in materials and geometries, multi-axis machining, efficient batch manufacturing, rapid prototyping, and seamless integration with CAD/CAM software program. These abilities make CNC milling machines quintessential gear in modern manufacturing, enabling the manufacturing of complicated components with pace, accuracy, and versatility.

2.4 Various types of CNC machines:

In the sector of mechanical engineering, there are numerous extraordinary types of CNC milling machines, each with its unique characteristics and programs. Here are some not unusual varieties of CNC milling machines:

Vertical Milling Machine: The vertical milling gadget is the maximum commonplace kind of CNC milling device. It has a vertical spindle orientation, with a slicing tool that movements vertically along the Z-axis. Vertical milling machines are versatile and suitable for a extensive variety of programs, inclusive of face milling, cease milling, drilling, and tapping.

Horizontal Milling Machine: In a horizontal milling system, the spindle is horizontally oriented, and the cutting device movements alongside the X-axis. Horizontal milling machines are recognized for their balance and pressure, making them perfect for heavy-obligation machining operations. They are frequently used for generating massive, flat surfaces, slots, and gear tooth.

Bed-Type Milling Machine: Bed-kind milling machines have a strong mattress that helps the workpiece and the milling head. These machines are characterized via their sturdy construction and excessive rigidity, making them suitable for heavy-responsibility machining of massive and complicated additives. Bed-kind milling machines are generally used in industries consisting of aerospace, car, and power.

Figure 2.4: Bed milling machines

Gantry Milling Machine: Gantry milling machines function a gantry shape that gives stability and rigidity. They have a horizontal spindle and a bridge-like shape that spans the workspace, taking into consideration the machining of huge workpieces. Gantry milling machines are frequently used for machining big aerospace components, molds, and heavy machinery components. Gantry type milling machine is depicted in figure 2.4.

Figure 2.5: Gantry milling machine

Turret Milling Machine: Turret milling machines have a turret-hooked up milling head that can rotate and pivot to one-of-a-kind angles, allowing for versatile and multi-sided machining operations. They are generally used for producing complex geometries, along with angles, curves, and abnormal shapes. The turret milling machine is depicted in the figure 2.4.

Figure 2.6: Turret milling machine

CNC Router: While now not strictly a milling device, CNC routers are extensively used in mechanical engineering for milling, slicing, and shaping operations on numerous materials. They make use of a rotating spindle and a transferring worktable to carve out tricky designs and lines. CNC routers are commonly used in woodworking, signal making, and prototyping.

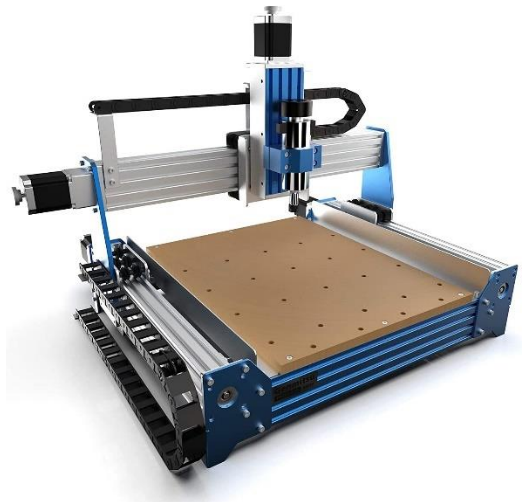

Figure 2.7: CNC Router

Five-Axis Milling Machine: Five-axis milling machines provide simultaneous manipulate of five axes of movement: X, Y, Z, and additional rotary axes. This permits the machining of complicated components from multiple angles and orientations, resulting in complicated geometries and high-precision surfaces. Five-axis milling machines are used in industries including aerospace, clinical, and automobile, in which complicated and contoured elements are required.

Benchtop Milling Machine: Benchtop milling machines are compact and transportable machines which might be appropriate for small-scale and hobbyist packages. They provide a smaller workspace but still offer correct and unique milling talents. Benchtop milling machines are typically utilized by DIY fans, small workshops, and educational establishments.

Figure 2.8: Benchtop CNC milling machine

These are only some examples of CNC milling machines commonly used in mechanical engineering. The preference of the gadget relies upon on elements consisting of the dimensions and complexity of the workpiece, the desired precision, the cloth being machined, and the unique machining operations wished. Each type of milling gadget has its benefits and is acceptable for extraordinary packages in the discipline of mechanical engineering.

2.4 Recent Advancement in CNC machining:

High-Speed Machining (HSM): High-speed machining is a current development in CNC milling technology that allows significantly quicker slicing speeds and decreased cycle instances. It makes use of advanced tool substances, coatings, and machining techniques to acquire better feed quotes and spindle speeds, resulting in advanced productivity and shorter machining instances.

Adaptive Machining: Adaptive machining includes real-time tracking and comments structures into CNC milling machines. It allows for computerized adjustments of cutting parameters based on sensor statistics, which includes cutting forces, temperature, and device put on. This adaptive approach optimizes machining situations, extends tool lifestyles, and enhances manner stability and efficiency.

Hybrid Additive Manufacturing: The integration of additive production (three-D printing) and CNC milling has caused the improvement of hybrid machines that combine each approach. These machines can build up fabric the use of three-D printing and then use CNC milling to precisely gadget the broadcast element. This hybrid method gives more design freedom, decreased material waste, and more advantageous part nice.

Intelligent Tooling Systems: Advancements in tooling systems have brought about the development of sensible equipment ready with sensors and information series talents. These tools provide actual-time information approximately reducing conditions, device wear, and tool lifestyles. The statistics accrued may be used for procedure optimization, predictive protection, and progressed usual machining overall performance.

Digital Twin Technology: Digital dual technology involves developing a virtual reproduction of the CNC milling system and simulating its operations in virtual surroundings. This enables engineers to optimize machining approaches, predict and prevent capacity problems, and examine one-of-a-kind machining strategies before imposing them at the real device. Digital dual technology complements productiveness, reduces downtime, and ensures green useful resource allocation.

Advanced Control Systems: CNC milling machines now function superior manipulate systems that comprise machine gaining knowledge of algorithms and artificial intelligence (AI). These systems can examine machining statistics in real-time, optimize slicing parameters, are expecting tool put on, and routinely adjust machining conditions for gold standard overall performance. Advanced manage structures enhance machining accuracy, productiveness, and performance.

Cloud-Based Manufacturing: Cloud-based manufacturing systems permit for faraway monitoring, control, and optimization of CNC milling machines. Machine facts, overall performance metrics, and analytics are transmitted to the cloud, imparting actual-time insights to operators, engineers, and managers. Cloud-primarily based manufacturing enhances collaboration, enables predictive protection, and enables continuous development in machining approaches.

Virtual Reality (VR) and Augmented Reality (AR) Integration: CNC milling machines are being integrated with VR and AR technology to enhance operator schooling, enhance machine setup, and streamline programming. VR and AR structures provide immersive reviews, permitting operators to visualise and have interaction with virtual device fashions, simulate machining operations, and carry out virtual inspections. This integration improves performance, reduces errors, and complements the overall person enjoy.

These recent improvements in CNC milling technology are revolutionizing the producing industry, allowing faster machining, smarter tooling, greater procedure control, and stepped forward productiveness. By harnessing those improvements, manufacturers can gain better levels of precision, efficiency, and competitiveness in their CNC milling operations.

2.5 Impact of CAD/CAM in CNC milling processes:

Enhanced Design Capabilities: CAD (Computer-Aided Design) software program allows engineers and architects to create difficult and complicated element geometries effortlessly. It offers a digital platform for developing 3-D models, defining dimensions, and specifying material houses. The integration of CAD with CNC milling machines allows specific translation of virtual designs into bodily components, ensuing in progressed accuracy and reduced manual mistakes.

Streamlined Workflow: CAM (Computer-Aided Manufacturing) software plays a crucial role in CNC milling procedures. It converts the CAD version into machine-readable code, referred to as G-code, which publications the CNC milling gadget all through the machining system. CAM software program optimizes device paths, calculates cutting parameters, and simulates machining operations, ensuring efficient use of resources and minimizing fabric waste. It streamlines the workflow from design to manufacturing, reducing lead instances and improving usual productiveness.

Design Iteration and Optimization: CAD/CAM integration facilitates layout iteration and optimization in CNC milling processes. With CAD software, designers can quickly modify and refine designs primarily based on comments or converting requirements. CAM software program permits simulation and evaluation of various machining techniques, permitting engineers to optimize device paths, reduce cutting time, and improve surface finish. The iterative design and optimization method made viable by means of CAD/CAM generation ends in stronger component quality and reduced development cycles.

Improved Accuracy and Precision: CAD/CAM structures make contributions to improved accuracy and precision in CNC milling methods. CAD software ensures specific design specs, even as CAM software program generates device paths that remember machine skills and tooling requirements. The integration of CAD/CAM with CNC milling machines allows steady and repeatable machining operations, reducing dimensional errors and reaching tighter tolerances. The end result is better nice components that meet stringent production standards.

Reduced Programming Time: CAD/CAM software program significantly reduces programming time for CNC milling machines. Instead of manually generating G-code, CAM software program robotically generates the code primarily based at the CAD version and predefined machining parameters. This automation removes the want for manual programming, reduces human errors, and quickens the programming process. With CAD/CAM integration, CNC milling machines may be quick set up for production, improving performance and responsiveness to changing demands.

Tool Path Optimization: CAM software program offers advanced device route optimization skills in CNC milling techniques. It analyzes elements such as reducing forces, fabric residences, and system constraints to optimize device paths for progressed machining efficiency and decreased tool put on. By minimizing pointless device actions and optimizing slicing techniques, device direction optimization complements productiveness, extends device existence, and reduces manufacturing prices.

Real-Time Monitoring and Control: CAD/CAM structures can be included with CNC milling machines to enable actual-time tracking and control. Sensor data, including reducing forces, spindle speed, and temperature, may be collected and analyzed in the CAD/CAM software. This statistics allows operators to monitor machining methods, detect anomalies, and make adjustments in actual-time, ensuring choicest overall performance and minimizing the threat of tool failure or element defects.

Documentation and Version Control: CAD/CAM integration affords complete documentation and version control capabilities. CAD software permits for correct and specific design documentation, which include component specifications, assembly instructions, and bill of materials. CAM software program continues a version history of machining applications, ensuring traceability and facilitating destiny changes or reproductions. This documentation and version control device enhances quality control, facilitates regulatory compliance, and simplifies renovation and troubleshooting tactics.

The integration of CAD/CAM in CNC milling techniques has revolutionized the producing enterprise, supplying superior layout abilities, streamlined workflows, improved accuracy, decreased programming time, device path optimization, real-time monitoring, and comprehensive documentation. This integration empowers producers to attain better productiveness, higher part nice, and accelerated competitiveness within the CNC milling area.

2.6 Difference between CNC milling and Manual milling:

CNC machining, or Computer Numerical Control machining, is a producing technique that makes use of computerized controls and programming to guide the movement of cutting gear and perform particular machining operations on a workpiece. It differs from conventional machining techniques in several key ideas:

Automation: One of the fundamental ideas of CNC machining is automation. CNC machines are controlled by laptop programs, which give instructions for the device's moves and operations. Once the program is installation, the gadget can execute the machining process mechanically, without the want for regular manual intervention. This automation improves performance, reduces hard work costs, and minimizes the capability for human mistakes.

Computer Control: CNC machines are managed by using laptop systems that interpret the programmed commands and convert them into particular moves and movements. The laptop manipulate lets in for specific manipulate over the gadget's moves, ensuring accurate positioning and constant effects. It additionally allows complicated machining operations that might be hard or impossible to attain with manual machining strategies.

Digital Design Integration: CNC machining integrates with pc-aided layout (CAD) and computer-aided manufacturing (CAM) software. CAD software is used to create virtual three-D models of the preferred component or element, even as CAM software program generates the toolpaths and machining instructions based totally at the CAD version. This digital integration lets in for seamless translation of design specifications into device commands, ensuring correct replication of the meant part.

Tooling Flexibility: CNC machining gives greater flexibility in tooling in comparison to conventional machining methods. CNC machines can accommodate quite a few reducing equipment, which includes drills, give up turbines, and lathes, which may be routinely changed at some point of the machining manner. This tooling flexibility permits for a extensive range of machining operations to be performed on a single device, reducing setup time and growing efficiency.

Multi-Axis Capability: CNC machines can function along multiple axes simultaneously, not like traditional machines that generally have limited motion skills. CNC milling machines, for example, can circulate the cutting tool alongside 3 or extra axes, enabling the creation of complicated geometries and features. This multi-axis functionality provides more versatility and opens up opportunities for machining tricky and customized components.

Precision and Accuracy: CNC machining gives considerably better precision and accuracy as compared to traditional machining techniques. The computer manipulate system allows for specific control over the system's moves and the cutting device's role, ensuing in steady and repeatable machining results. This precision is specially important for industries that require tight tolerances and notable completed merchandise.

In precis, the concepts of CNC machining contain automation, pc manage, virtual layout integration, tooling flexibility, multi-axis capability, and more suitable precision. These principles distinguish CNC machining from traditional machining techniques, offering progressed efficiency, accuracy, and flexibility inside the manufacturing process.

2.7Applications of CNC milling:

CNC milling machines are extensively used in numerous industries and sectors due to their versatility, precision, and automation talents. Some of the key industries where CNC milling machines find widespread packages include:

Aerospace Industry: The aerospace enterprise relies closely on CNC milling machines to produce crucial additives and parts. These machines are used to gadget complex geometries located in plane structures, engine additives, turbine blades, and different aerospace-related elements. CNC milling ensures high precision and repeatability, taking into consideration the production of lightweight and aerodynamically efficient components.

Automotive Industry: CNC milling machines play a critical position inside the automotive enterprise for the producing of various additives, which include engine blocks, cylinder heads, transmission components, brake components, and interior and outdoors trim components. With CNC milling, automobile manufacturers can obtain tight tolerances, complex shapes, and particular floor finishes, contributing to stepped forward performance, safety, and aesthetics.

Medical Industry: CNC milling machines are appreciably used in the scientific enterprise for the production of clinical devices, implants, surgical contraptions, and prosthetics. These machines can create intricate and custom designed components with high precision, ensuring proper healthy, capability, and biocompatibility. CNC milling permits for the manufacturing of affected person-specific implants and scientific devices, contributing to advancements in healthcare and personalized medication.

Electronics Industry: The electronics industry benefits substantially from CNC milling machines for the fabrication of electronic components, circuit boards, and enclosures. These machines can as it should be mill intricate styles, drill precise holes, and create nice traces on circuit forums. CNC milling allows the manufacturing of super digital additives with tight tolerances, ensuring reliability and overall performance in digital gadgets and structures.

Mold and Die Industry: CNC milling machines are broadly used inside the mold and die enterprise for the manufacturing of molds, dies, and tooling. These machines can exactly mill complex shapes and lines required for molding and forming approaches. CNC milling allows for the creation of tremendously accurate and repeatable molds and dies, decreasing lead instances and improving average productiveness in the production of plastic components, metal additives, and different products.

Prototyping and Rapid Manufacturing: CNC milling machines are essential in prototyping and rapid manufacturing strategies. They allow the fast and accurate production of prototypes, permitting designers and engineers to check and validate their designs before mass manufacturing. CNC milling machines can swiftly create functional prototypes and small batch productions, facilitating iterative design methods and accelerating time to market.

Jewelry and Artistic Industries: CNC milling machines are also utilized in the rings and inventive industries for the creation of elaborate and distinctive designs. These machines can accurately mill precious metals, gemstones, and other materials, bearing in mind the manufacturing of problematic rings portions and creative sculptures. CNC milling allows artists and jewelry designers to bring their innovative visions to life with precision and consistency.

In addition to those industries, CNC milling machines are also used in sectors which includes protection, electricity [3], woodworking, education, and studies. Their huge variety of applications and adaptability make them a fundamental device in modern-day production, allowing the production of complicated, customized, and topnotch additives throughout numerous industries.

Problem Statement

A 3-axis CNC milling machine may not be able to produce complex parts that need to be machined at different angles and orientations efficiently. This constraint may increase production time, reduce precision, and reduce efficiency, which would ultimately result in higher costs and possibly lower-quality goods. While a 3-axis machine is appropriate for simpler parts, it might not be the greatest choice for more elaborate components that call for more difficult machining procedures.

The limitation of 3-axis CNC milling machines in terms of producing intricately shaped, complex items is their limited capability. This occurs as a result of their inability to move the cutting tool in a few directions at once, which can lead to longer production times and less accurate machining. As a result, businesses can find it difficult to make all the parts they need using a 3-axis CNC milling machine and might need to spend money on a more sophisticated equipment to keep up with market demand.

Thesis Statement

The 3-axis CNC milling machine is still a popular and economical choice for producers who place a premium on efficiency and accuracy in their production processes, despite its limitations in the area of machining intricate parts with complex geometries. 3-axis machines may successfully produce a variety of products by utilizing their strengths and putting relevant procedures and tooling strategies into practice, making them a crucial tool in contemporary production.

The 3-axis CNC milling machine is a powerful tool for manufacturing a wide range of parts, but its limitations in terms of complex geometries and multi-directional machining make it a less versatile option compared to 4 or 5-axis machines, highlighting the need for careful consideration of the machining requirements and production goals before investing in a particular machine.

<u>CHAPTER 3: METHODOLOGY</u>

To design our milling machine, we start with defining our specific requirements and objectives for the 3-axis milling machine. By considering factors such as the maximum workpiece size, desired accuracy and precision, cutting capabilities, spindle power and speed, tooling options, the material we want to cut, safety factors for the machine as well as safety measures for the operators. Keeping in mind all these parameters we begin by determining its specific dimensions and our budget.

We start by studying existing 3-axis milling machine designs to understand their structural configurations, mechanical components, and control systems. This research provided us insights into industry-standard practices and help us identify areas for improvement and innovation.

We begin with the mechanical design by creating a structural framework that provides stability and rigidity. Consider factors such as material selection, frame design (such as gantry, bridge, or column), linear motion systems (such as ball screws or linear guides), and the overall size and footprint of the machine.

Next, we design the axis mechanism for each of the three axes (X, Y, and Z). We determine the type of motion system that suits our requirements, such as linear guides, ball screws, or rack and pinion drives. We select suitable motors, drives, and feedback systems for precise and controlled movement.

We determine the type of spindle we need based on the materials and cutting operations we plan to perform. Consider factors such as power, speed range, and tool holding options (such as collets or automatic tool changers). we design the tooling system to accommodate the desired cutting tools.

For designing the electrical system, including wiring, power distribution, and safety features. We select appropriate motor drives, controllers, and feedback systems for each axis. Integrate a suitable control system, such as mech 3, to translate digital instructions into precise machine movements.

In order to generate the CNC programs that will control the machine we choose mech 3 controller. We consider using CAD/CAM software to create and optimize tool paths for efficient machining. Ensure compatibility between the software, controller, and machine specifications.

We also Incorporate safety features into our machine design to protect both the operator and the equipment. This include emergency stop buttons, limit switches, and safety interlocks.

After the initial design is complete we build a prototype of the 3-axis milling machine. We tested its functionality, accuracy, and performance to identify any design flaws or areas that need improvement. We make necessary modifications based on the test results.

After successful prototyping and testing, we finalize the design and prepare for manufacturing. We determine the most suitable manufacturing methods and processes for producing the components of the milling machine. We ensure that the quality control measures are in place during production.

Once the machine is manufactured, we install it in the desired location and calibrate all the axes for accurate positioning. We test the machine with different cutting operations and verify its performance against the defined requirement.

3.1 Design Consideration

The key components of a 3-axis milling machine are the machine frame, spindle, worktable, linear guides, and control system. The machine frame provides the structural support for the machine and should be made of a rigid and durable material, such as cast iron or steel. The spindle is responsible for rotating the cutting tool and should be designed for high speed and torque. The worktable holds the material being machined and can be either fixed or adjustable. Linear guides are used to guide the cutting tool and workpiece along the X, Y, and Z axes.

To improve accuracy while keeping costs low, some design considerations include:

A. Choosing the appropriate linear guides and ball screws: High-quality linear guides and ball screws can significantly improve accuracy, but they can also be expensive. Choosing the right components for the specific application can help keep costs down while still achieving the desired accuracy.

B. Implementing closed-loop control: Closed-loop control systems use feedback from sensors to adjust the position of the cutting tool and workpiece in real-time, which can improve accuracy. This can be achieved using inexpensive sensors such as optical encoders.

C. Reducing backlash: Backlash, or the play in the mechanical components of the machine, can reduce accuracy. Using low-backlash components, such as preloaded ball screws, can help improve accuracy.

D. Minimizing vibration: Vibration can also reduce accuracy. Designing the machine to minimize vibration, such as by using a rigid frame and high-quality spindle bearings.

E. Frame and Base: The frame and base of the milling machine provide the foundation for the entire system. It should be strong and rigid enough to support the machine's weight and withstand the forces generated during milling.

F. Spindle and Tooling: The spindle is responsible for holding the cutting tool, and it is critical for achieving accurate milling results [4] [5] [6] [7]

3.1.1 Spindle Selection

When it comes to CNC jobs, selecting the appropriate spindle is of utmost importance. The vast array of options and numerous factors involved can be overwhelming. In this comprehensive guide, I aim to simplify the process of choosing a spindle for your CNC router by providing you with all the necessary information. The key to selecting the right spindle lies in achieving a harmonious balance between its speed, power, and torque. Once you have determined the ideal values for these three parameters, the remaining aspects such as cooling mechanism, construction, and motor type become much easier to consider. [8]

To ensure optimal performance with your material, opt for a CNC spindle that possesses the appropriate RPM, power, and cooling capabilities. For working with wood and aluminum, a spindle operating at 24,000 RPM with a power of 1kW would be ideal [9]. On the other hand, when dealing with steel, a range of 15,000-18,000 RPM and a power output of 5.6 kW are recommended for tool sizes up to 12mm [10].

Material	Max. RPM	Tool size	Power (kW)
Plastic, wood, aluminum	24,000	Up to 5 mm	0.8
		Up to 8 mm	1
		Up to 12 mm	3.3
		Up to 16 mm	5.6
Steel	15,000 - 18,000	Up to 10 mm	3.3
		Up to 12 mm	5.6
		Up to 16 mm	7
		Up to 20 mm	10

Fig 3.1 shows spindle selection criterion for material

3.1.2 Spindle Specifications

The unique properties and hardness of various materials necessitate specific cutting techniques when it comes to CNC machining. As a result, the type of spindle required is determined by the materials you plan to work with [11]. By carefully selecting the most appropriate metal for CNC machining, you can enhance the overall precision and quality of the cuts produced by your spindle. In our case, we will be conducting machining operations on wood surfaces as well as aluminum and its alloys [12]. For these applications, a spindle with a rotation speed of 24,000 RPM and a power output of approximately 1.5 kW is recommended [13].

3.1.3 AC vs DC Spindle

For hobby use, DC spindles are a cost-effective option compared to AC spindles. While it's true that DC motors offer better starting torque than AC motors, this factor becomes irrelevant in the CNC realm since spindles always start without any load [14]. DC spindles can be categorized as either brushed or brushless. Brushed motors are more budget-friendly than brushless motors, but they require periodic brush replacements and tend to have more vibrations. If your intention is to use the spindle primarily for engraving purposes, a brushed DC spindle may suffice. However, for other applications where a smooth finish is desired, it is advisable to opt for a brushless motor [15].

Controlling the speed of a DC spindle can be achieved through a PWM (Pulse Width Modulation) circuit, which is simpler and less expensive compared to the driver circuit required for AC spindles. However, it's important to note that the torque of DC spindles is optimized within specific speed ranges, making them suitable only if your project's speed requirements fall within a narrow range. Generally, DC spindles for CNCs have lower power output as DC circuits are limited by the voltage they can handle. Consequently, they are better suited for low-power applications such as engraving and carving wood [16].

Figure 3.2: AC spindle B100 FANUC

When it comes to selecting a spindle, choosing an AC spindle becomes significant if your project necessitates a powerful spindle. AC spindles are suitable for a wide range of applications, although cost may be a limiting factor. These spindles deliver optimal performance across various speeds, making them the ideal choice when working with different materials and tools. However, controlling the speed of AC spindles requires a VFD (Variable Frequency Drive), which is more expensive compared to the controller used for DC spindles [17].

If your budget allows, opting for an AC spindle provides greater flexibility. Nevertheless, based on our project requirements, we conclude that a high-torque DC spindle is the most suitable choice.

3.1.4 Build of Spindle

It is crucial to avoid spindles that lack a metal construction, as they are unable to withstand the stress and vibrations associated with machining, ultimately resulting in breakage. Spindles are a primary source of vibrations in CNC mills, underscoring the importance of selecting a spindle with a robust body that offers enhanced rigidity. When working with materials such as wood or other soft materials, an aluminum construction spindle like the Genmitsu GS-775M 20000RPM CNC Motor would be sufficient for engraving and cutting tasks. However, for CNC milling of hard metals, it is preferable to choose a steel or castiron spindle, albeit at a higher cost compared to aluminum-bodied spindles. Opting for a well-constructed spindle ensures longevity and durability in its performance.

3.1.5 Dimensions of Spindle:

Selecting the right spindle size is essential as it dictates the size of the tool you can utilize. In standard spindles, the diameter of the shaft should be compatible with the collet that accommodates the intended tools. In the case of ATC (Automatic Tool Changer) spindles, the taper should be appropriate for a proper fit of the tool. In America, the CAT40 type is widely used for ATC spindles, capable of securely holding tools with a shank diameter of up to ½ inch.

3.1.6 Spindle Bearings:

The runout of a CNC router is significantly influenced by the bearings utilized. The stability of the spindle shaft during operation depends on the quality and quantity of these bearings. Larger bearings are employed in spindles with higher power outputs, as the spindle size increases proportionally. As the spindle rotates, the balls within the bearings experience pressure against the bearing walls. This pressure intensifies at higher speeds, potentially generating excessive heat in high-speed applications. To mitigate this issue, it is advisable to select a spindle equipped with ceramic bearings, particularly for very high-speed applications that necessitate both high power and spindle speeds.

In the case of CNC spindles intended for steel machining, preloaded bearings are essential. Without preloaded bearings, the spindle lacks the necessary rigidity to effectively cut through hard materials. Therefore, the inclusion of preloaded bearings is crucial to ensure proper performance and cutting capability when dealing with challenging materials like steel.

3.1.7 Speed (RPM) of Spindle:

The spindle speed plays a crucial role in determining both the material removal rate and the final surface finish of the product. If your milling tasks involve wood, plastic, composite, or aluminum, a high-speed spindle with a maximum speed of 24,000 RPM is recommended for optimal performance [18].

However, for materials such as thermoplastics, steel, and other ferrous metals, low-speed spindles with good torque ranging between 6,000 and 15,000 RPM should be used. Softer materials generally require higher spindle speeds to achieve a satisfactory finish compared to harder materials. It's important to note that the required speed also depends on the type of tool being used. For example, carbide tools typically require higher RPMs compared to High-Speed Steel (HSS) tools. Additionally, certain tools may have coatings that are only activated within specific speed ranges [19].

If you intend to use small tools, a high-speed spindle is preferable. Conversely, if you plan to utilize larger diameter tools, a low RPM spindle is more suitable. However, if your project involves using both small and large diameter tools, selecting a spindle with a wide speed range becomes necessary.

It is worth noting that higher RPM allows for faster completion of the machining process, but it may result in a less refined finish. As a general rule of thumb, it is recommended to use high-speed settings for roughing operations and switch to lower speeds for finishing passes. Online calculators are available to assist in determining the appropriate speed and feed rates for your specific machining requirements [20].

3.1.8 Torque of Spindle:

The power of a spindle directly impacts the cutting speed, while the torque determines the ability to cut through harder materials. It is possible to enhance torque by utilizing gears, although this may result in a compromise on speed. When working with soft materials such as wood, plastic, and aluminum, the torque requirements are generally lower. On the other hand, when dealing with hard materials like steel and other ferrous metals, sufficient torque at lower speeds is essential to maintain effective cutting.

3.1.9 Concluding the Spindle:

It is essential to carefully evaluate all the aforementioned factors and select a spindle that aligns with your specific requirements. In terms of hobby CNC applications, both Mophorn and Huanyang spindles are reputable options to consider. For a comprehensive review of the top CNC spindles currently available, I recommend reading the guide titled "Best CNC Spindles in 2022." [2]This resource will provide valuable insights and assistance in making an informed decision.

Figure 3.3: Spindle

Now the selection process heading towards the motor that which one is best suit for the project and the desired materials machining.

3.1.10 Servo vs Stepper Motor:

Servo cars and stepper automobiles are commonplace forms of automobiles utilized in CNC milling machines. Here are the important thing differences between them:

3.1.10.1 Principle of Operation:

Servo Motor: A servo motor operates primarily based on a closed-loop control gadget. It makes use of feedback from position sensors (along with encoders) to constantly modify its rotational function and velocity. The servo motor gets indicators from the controller and adjusts its role to hold precise movement.

Stepper Motor: A stepper motor operates based on an open-loop manage system. It moves in discrete steps, wherein each step corresponds to a set angular displacement. The stepper motor gets pulses from the controller, inflicting it to rotate a predetermined range of steps.

Control and Precision:

Servo Motor: Servo motors offer high precision and accuracy in CNC milling applications. The closed-loop manipulate machine allows for accurate positioning and velocity control. Servo motors can dynamically adjust their moves, making them suitable for complicated machining tasks that require particular and easy motion [22].

Stepper Motor: Stepper motors offer proper positional accuracy, however they're now not as particular as servo cars. Stepper vehicles pass in discrete steps, so their accuracy depends at the step length and the controller's capacity to as it should be command the preferred variety of steps [23]. However, they lack the capability to dynamically adjust their motion like servo automobiles.

3.1.10.2 Torque and Power:

Servo Motor: Servo cars offer excessive torque abilities, making them appropriate for heavy-obligation machining operations. They can generate a big quantity of torque at low speeds, taking into account green milling of difficult substances. Servo motors have accurate strength transport characteristics at some stage in their velocity range.

Stepper Motor: Stepper cars have decrease torque as compared to servo vehicles. They are better ideal for programs that require decrease torque and slight speeds. Stepper cars may lose torque at better speeds due to their open-loop manipulate system, limiting their suitability for high-velocity machining.

3.1.10.3 Response and Dynamic Performance:

Servo Motor: Servo motors have high-quality dynamic performance and reaction. They can quick reply to modifications in the commanded position or speed, making an allowance for speedy acceleration and deceleration. Servo cars are well-proper for programs that require speedy and particular moves.

Stepper Motor: Stepper vehicles have slower response and dynamic overall performance compared to servo cars. They are not as nicely-proper for excessive-pace machining or applications that require quick changes in movement. Stepper vehicles have a confined capacity to boost up and slow down swiftly.

3.1.10.4 Cost:

Servo Motor: Servo vehicles are commonly greater high priced than stepper cars. They involve extra complicated manage structures, remarks mechanisms, and higher-great components. The added value is justified via their better precision, dynamic performance, and versatility.

Stepper Motor: Stepper motors are generally more price-powerful in comparison to servo vehicles. They have a easier layout, do not require position feedback gadgets, and are simpler to govern. Stepper automobiles are a popular desire for programs wherein precision is not as critical, and price is a substantial consideration.

The preference among servo motors and stepper automobiles in a CNC milling gadget relies upon at the unique requirements of the utility. Servo vehicles are favored for excessive-precision machining, complex moves, and demanding packages. Stepper vehicles are appropriate for less difficult machining responsibilities, cost-sensitive packages, and situations in which positional accuracy is much less crucial.

3.1.10.5 Cessation About Motor:

The debate between stepper motors and servo motors is ongoing in the CNC manufacturing industry. However, the right choice depends on your specific requirements. Servo motors offer higher precision, while stepper motors are more affordable and have a longer lifespan.

If precision and high torque are not crucial factors for your application, the stepper motor is a cost-effective choice. However, if budget is not a constraint and you can handle the frequent replacement demands of servo motors, they might be the better option for you.

3.1.10.6 CNC Router Size:

The size of the CNC router is a key consideration when deciding which motor to use. For a CNC router with a small footprint and limited work area, a stepper motor is generally more suitable than a servo motor. Stepper motors are commonly used in CNC routers with a maximum cutting area of 4' x 4', including some entry-level industry CNC routers with cutting areas of 4' x 8' and 5' x 10' to keep costs down. In larger CNC routers, where gantries are larger and prone to flexing, a servo motor is a more appropriate choice due to the need for a sturdier construction.

3.1.10.7 Motor Size and Control:

Another factor to consider is the physical size of the motor. Servo motors are larger and heavier compared to stepper motors due to their complex design. For smaller CNC applications, stepper motors are generally a better fit.

In terms of motor control, stepper motors move a predetermined number of steps with each pulse, and the controller has no knowledge of whether the motor has actually moved. On the other hand, servo motors have closed-loop control, where the motor sends position and direction information back to the controller. This allows the controller to detect any errors that may have occurred, which can be crucial when working with expensive workpieces.

For example, let's say you are making a 2-inch cut on an expensive workpiece, and something causes a jam in your linear drives or gantry. If you are using stepper motors, the motor may skip steps and continue cutting, resulting in a cut that falls short of the desired length. In such cases, you would need to discard the workpiece and start over with a new one.

In contrast, if you are using servo motors, the controller is aware of the actual movement of the axis and will continue the cut until it reaches the desired length. However, it is important to note that servo motor controllers are more complex and expensive compared to stepper motor controllers. Another option to achieve good results at a lower cost is to use closed-loop stepper motors. These motors offer the characteristics of stepper motors with the added benefit of error prevention. For example, ToAUTO offers a closed-loop NEMA 23 stepper motor with positional encoders that provide feedback for position correction.

So, if you require precise cuts on workpieces where any error can be disastrous, servo motors are the ideal choice. However, it is worth noting that programming for servo motors can be more challenging compared to programming for stepper motors, making steppers a better choice for beginners. shown in fig. [2.5].

Figure 3.4: Stepper Motors

3.1.10.8 Speed (RPM) & Torque:

Stepper motors are efficient at speeds of 1,200 RPM or lower and can generate high torque at low speeds. Typically, stepper motors have a holding torque ranging from 30 oz-in to 1500 oz-in. However, as the motor speed increases, the torque decreases, sometimes up to 80% at very high RPM.

On the other hand, servo motors operate at speeds exceeding 2000 RPM and offer much higher torque ratings than stepper motors. This makes them faster than stepper motors. One of the advantages of servo motors is their ability to provide consistent torque throughout their speed range. Servos have superior torque performance compared to steppers, making them suitable for applications requiring heavy spindles.

If you are using heavy gantries and a substantial spindle, considering servos is advisable to achieve fast speeds. Additionally, servos perform better under dynamic loads, meaning they maintain consistent performance across different materials and cutting settings without slowing down under varying loads. However, it is important to note that steppers can still be a suitable choice for large CNC machines. For instance, a NEMA 34 stepper motor can handle a 7 hp spindle on an aluminum and steel plate CNC router while achieving rapid speeds of around 1,000 inches per minute.

Another significant difference between the two types of motors is the time required to make cuts. Motors cannot instantly reach full speed; they take time to ramp up and slow down. When it comes to acceleration and deceleration, servos are slightly faster than stepper motors, with a difference of a few milliseconds. This slight difference is negligible for parts with quick runs and minimal changes in cut direction. However, in cases where the spindle needs to change direction frequently, those milliseconds add up, resulting in a significant disparity in project completion time between servos and steppers. If speed of production is crucial in a production environment, choosing servos is recommended.

The comparison graph shows the curves of the stepper and the servo motor with the variation of the torque vs the RPM of motor is shown in fig. [2.6].

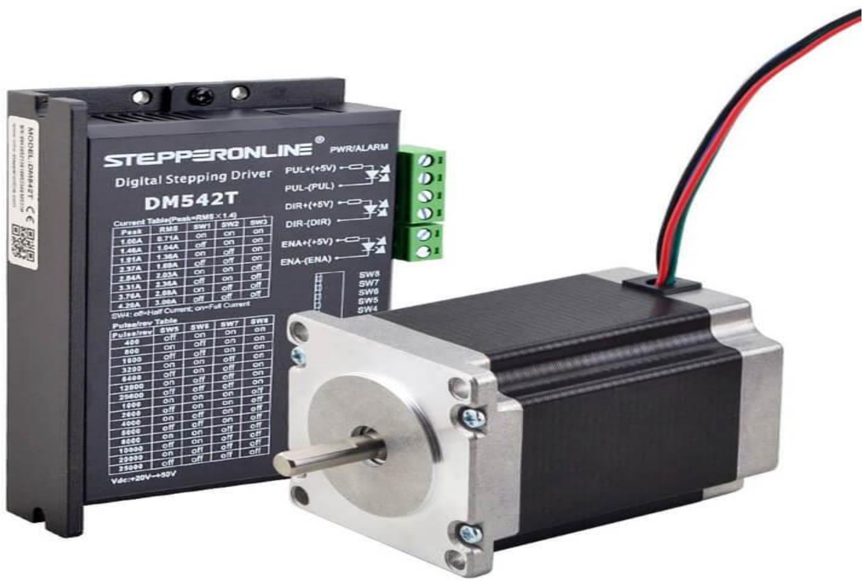

Figure 3.5: Motor with controller

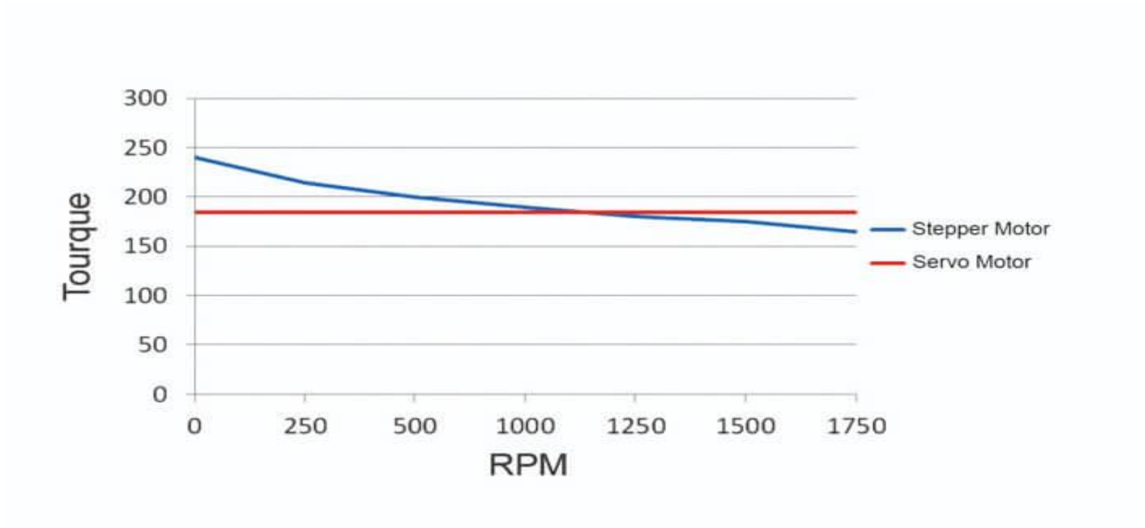

Figure 3.6: Torque vs RPM of both Servo & Stepper motor

3.1.10.9 Holding Torque:

The holding torque of a motor determines its ability to maintain its position when the coils are energized. In the case of a stepper motor, it will remain stationary without an input signal as long as the torque on the motor shaft is below the holding torque. On the other hand, a servo motor has negligible holding torque. So, how does a servo motor hold the load in place?

A servo motor utilizes a feedback mechanism to detect any change in shaft position and instantaneously corrects the position. It oscillates at the held position, but these oscillations are extremely small. However, when servos are not properly tuned, they can produce vibrations and noise when holding a load in a stationary position. Holding torque is a significant consideration, especially when holding a load vertically, such as with the spindle on the Z-axis. This becomes particularly important when using ball screws for linear motion.

Ball screws have low internal friction and can be back-driven. This means that if a ball screw is used on the Z-axis and the spindle is lifted upwards, the weight of the spindle can pull the ball screw back down. To prevent this, the motor coupled to the linear motion component needs sufficient holding torque to prevent the load from back-driving the linear motion components. Using a stepper motor with adequate holding torque is a straightforward and effective solution. Servos can also perform this task well, but it requires careful tuning of the controller to prevent unnecessary vibrations and noise that can potentially damage other components.

3.1.10.10 Input Power and Efficiency:

Stepper motors operate on DC power and typically work at their full potential regardless of the load. They have an efficiency of around 70%. On the other hand, servos can operate on either AC or DC supply and draw power proportional to the load they carry [24]. This means that servos can achieve efficiency levels of 80-90%.

Power consumption is a factor to consider, especially in a production environment where the extra cost of servos can be offset by savings in power bills. However, if your production volumes are low and the loads are relatively small, investing in servo motors may not provide a significant cost advantage, making stepper motors a better choice [25].

3.2 Final Motor Selection:

Considering the features discussed above will assist you in choosing the appropriate motor for configuring your CNC router. Your selection primarily depends on your budget and the type of work you intend to do. For applications that do not require ultra-high precision, such as woodworking, stepper motors are a suitable choice. It's worth noting that most CNC routers priced under $25,000 utilize stepper motors rather than servo motors.

Stepper motors can generally provide feed rates ranging from 50 to 1000 inches per minute, while servos can go beyond 2500 inches per minute. If you require very high precision and high production speeds, servo motors are the preferred option. Alternatively, you can consider closed-loop stepper motors, which are effective in preventing errors caused by missed steps and can be a cost-effective solution when working with expensive workpieces.

3.3 Controllers and Programs:

- Microcontroller (PIC16F877 microcontroller)
- 16 MHz crystal
- A crystal oscillator is an electronic oscillator circuit that uses mechanical resonance of a vibrating crystal of a piezoelectric material to create an electric signal of precise frequency. This frequency is often used to keep track of time.
- ULN2003 (The ULN2003 is used to raise the microcontroller output current from 25 mA to 500 mA to be fed to the stepper motors drivers)
- PC817 opt-coupler (The PC817 opt-coupler is used to protect and isolate the microcontroller from any electrical problem and noise came from the interface unit)
- Two motors drivers
- Power supply unit

While most of the time three software are used

1. SolidWorks
2. ACAD software is required which provide platform to make desired 3D geometry, with easy-to-use interface and should be able to generate DXF file.
3. Lazy CAM by Art soft
4. It is required to convert DXF file into G-codes.
5. Mach3 by Art soft
6. Mach3 will read the g-code and output signals to the machine that invoke the driver and motors. Mach3 can also control such mechanisms as coolant, spindle speed, limit switches, e-stop, other axes, and many others.

7. Mach3 turns a typical computer into a CNC machine controller. It is very rich in features and provides a great value to those needing a CNC control package. Mach3 works on most Windows PCs to control the motion of motors (stepper & servo) by processing G-Code.

3.4 Spindle Requirement for CNC Milling:

To calculate the spindle power and cutting force, we make certain assumptions. And we use KENNAMETAL [2] website to calculate it. Spindle slicing pressure refers back to the force exerted by using the rotating reducing device (commonly an quit mill) on the workpiece during CNC milling operations. The reducing pressure is influenced by different factors, together with the cloth being machined, the form of slicing tool, the feed fee, the depth of reduce, and the cutting conditions. High slicing forces can reason deflection or vibration within the milling gadget, affecting machining accuracy and floor end. It is essential to consider and optimize slicing forces to ensure a success and green milling operations.

Spindle power refers to the quantity of electricity required by way of the spindle motor to force the reducing tool at some point of CNC milling operations. The spindle energy is determined by using factors including the cutting tool's fabric and geometry, the reducing velocity, the feed charge, the depth of reduce, and the material being machined. Higher cutting speeds, feed prices, and depths of reduce usually require greater spindle energy to maintain efficient slicing performance.

The spindle motor's electricity rating is an vital consideration when deciding on a CNC milling gadget, as it wishes to provide sufficient electricity to drive the reducing device and triumph over the slicing forces encountered during machining. Insufficient spindle power can result in bad cutting performance, extended tool wear, and capacity damage to the milling system. It's crucial to observe that the unique values for spindle slicing pressure and power can vary significantly relying at the unique machining parameters, tooling, and workpiece materials. These values are usually determined via reducing force models, empirical information, or device producer guidelines unique to the milling operation handy.

3.5Assumptions:

3.5.1 workpiece material:

We assume Aluminum as our workpiece. from website MATWEB [3] When milling aluminum, the usage of CNC milling machines, numerous concerns come into play due to the unique homes of the fabric. Here are a few key points to maintain in thoughts:

Tool Selection: Choosing the precise cutting tool is critical whilst milling aluminum. Carbide quit mills are generally used because of their high hardness, warmness resistance, and ability to face up to the high reducing speeds associated with aluminum machining.

Cutting Speed and Feed Rate: Aluminum is a surprisingly gentle cloth compared to other metals, bearing in mind better slicing speeds. However, it's miles important to balance the cutting velocity with the feed price to save you immoderate warmth generation and tool put on. Increasing the feed price can help maintain chip evacuation and prevent chip re-cutting.

Chip Evacuation: Aluminum produces lengthy, continuous chips all through milling. Ensuring powerful chip evacuation is vital to save you chip clogging and capability device breakage. Proper chip evacuation can be carried out with the aid of the usage of adequate coolant or lubrication, optimizing reducing parameters, and using chip evacuation techniques which includes thru-tool coolant or air blast.

Work holding: Aluminum can be vulnerable to vibration at some point of machining due to its decrease stiffness in comparison to metal. Ensuring secure work holding is important to reduce workpiece motion and hold dimensional accuracy. Options including vices, clamps, or specialized furniture designed for aluminum milling ought to be taken into consideration.

Surface Finish: Aluminum has a bent to generate built-up part (BUE) during milling, which can have an effect on surface end. Employing appropriate cutting parameters, tool coatings, and lubrication can assist limit BUE and obtain a smooth floor finish.

Heat Dissipation: Aluminum conducts heat nicely, so effective warmth dissipation is necessary to prevent heat buildup at some point of milling. Adequate cooling and lubrication strategies, such as the use of coolants or air blasts, assist use up heat and prolong tool life.

Tool Wear and Maintenance: Despite being a rather smooth material, aluminum can cause tool put on due to the presence of abrasive debris and the era of heat. Regular tool inspection, upkeep, and tool life monitoring are essential to ensure most fulfilling overall performance and prevent device failure.

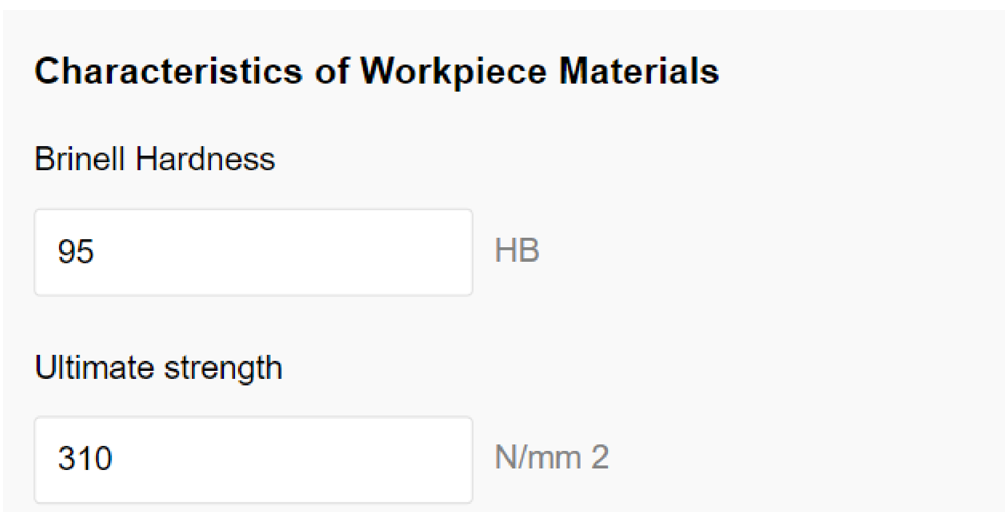

Figure 3.7: Traits of workpiece materials

3.6 End mill tool

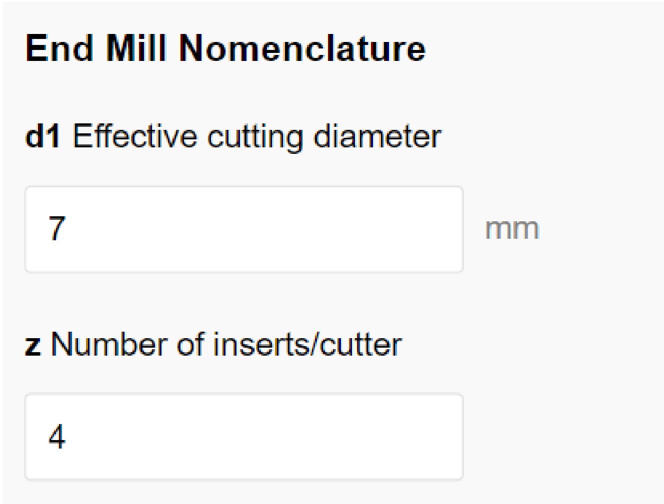

Figure 3.8: Nomenclature of End Mill

3.7 Machining conditions

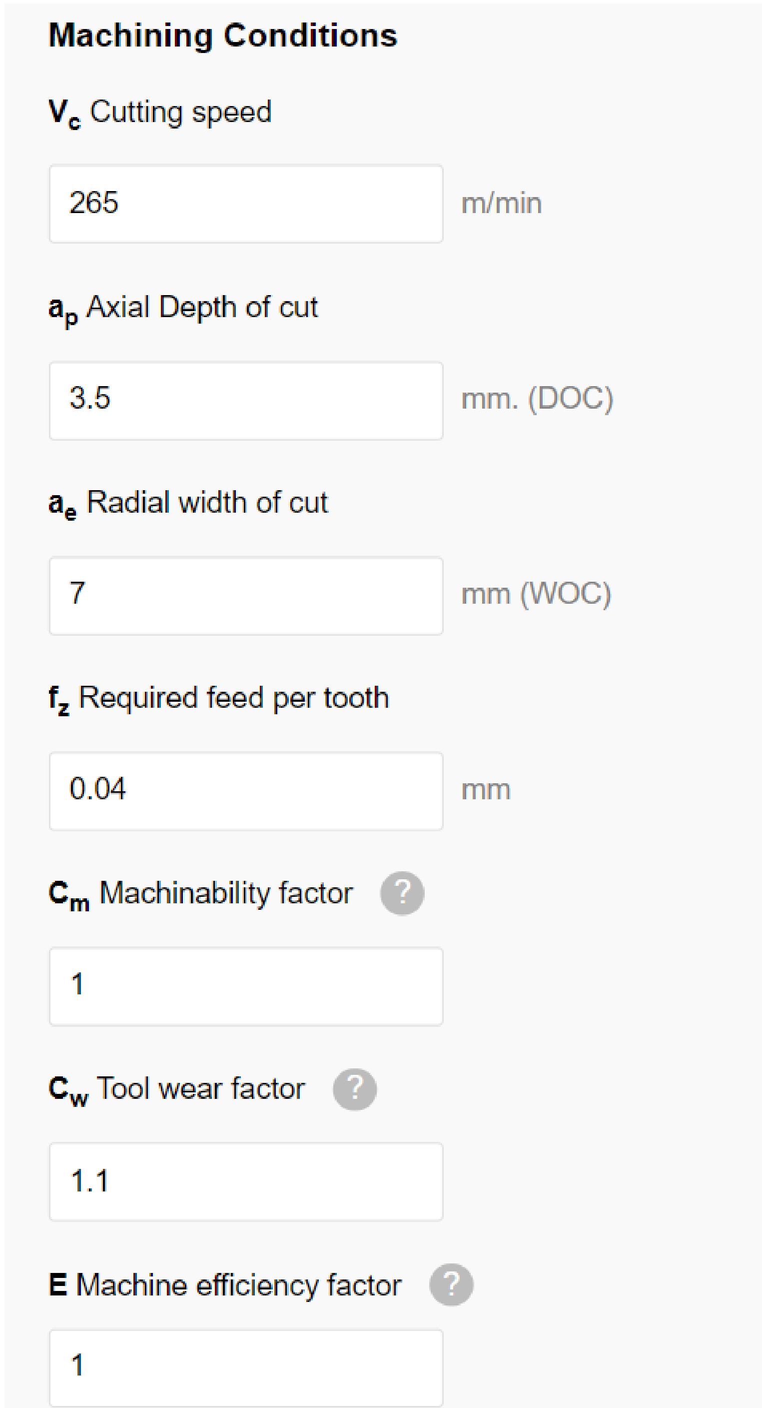

Figure 3.9: Machining specifications

Calculated Machining Conditions

n Spindle speed	**12050.3** RPM
V_f Feed rate	**1928.05** mm/min (no productivity formula)
Reduced feed per tooth	**0.04** mm/min (chip load at the cut)
F_p Feed rate	**1928.1** mm/min (with productivity formula)
Q Metal removal rate	**472.384** cm3/min
A Cross-sectional area of chip	**0.14** mm^2
z_c Number of flutes in the cut	**2**
a_e/d_1 Ratio of radial width of cut to cutting diameter	**1**

Figure 3.10: Calculated conditions

3.8 Cutting Force

Calculated Required Power

F_t Tangential cutting force	**95.48** N
T Torque at the cutter	**0.33** Nm

Figure 3.11: Theoretical Required power

3.9 Spindle Power

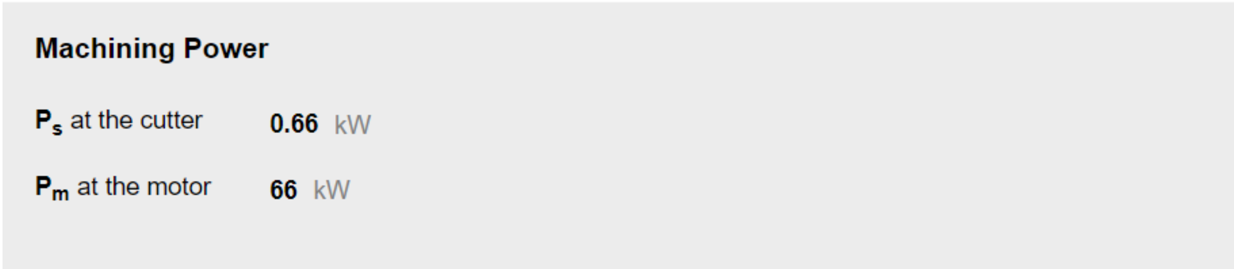

Figure 3.12: Theoretical Spindle Power

3.10 Spindle Selection

We don't have a graph of 800W spindle, but we have graph of 1.5 kW DC spindle. From it we can assumed the power of our spindle

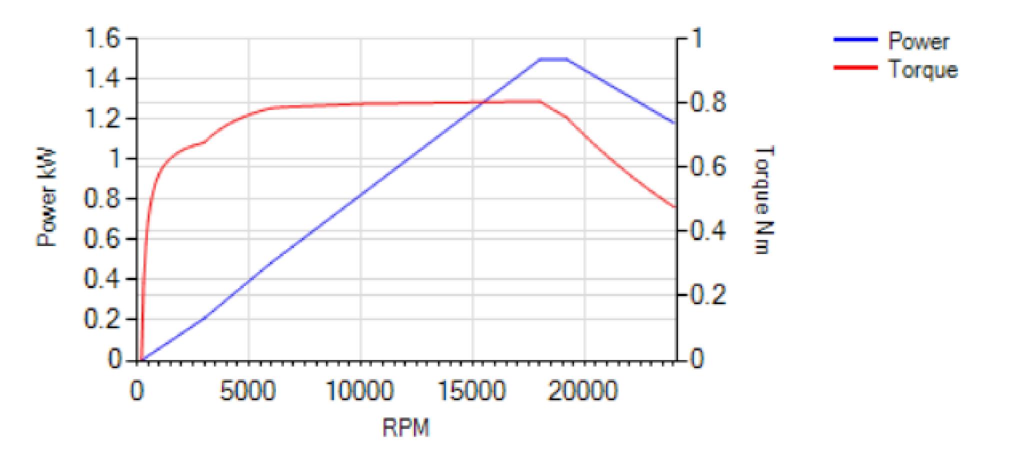

Figure 3.13: Theoretical Spindle Selection

From graph we can see that power increase with speed but it does reach its maximum value at maximum speed but before it. For 1.5 KW it reaches maximum power at around 18000 rpm. So, our 800W spindle range if from 0 to 20000 rpm so we assume 14000 to optimum speed for power. So, power at 12000 rpm will be calculated as

$$\boldsymbol{Power = m \times Speed + C}$$

M= slope

C = y intercept

$$Power = \frac{800}{14000}\ speed + 0$$

$$Power = \frac{2}{35} \times speed$$

Power at 12000 rpm

$$Power = \frac{2}{35} \times 12000 \approx 686\ W$$

Since

$$\mathbf{686W > 660\ W}$$

So our spindle have enough power to mill the workpiece with above condition.

3.11 Cutting force Verification:

From research paper

Analysis of the Effect of Trochoidal Milling on the Surface Roughness of Aluminium Alloysafter MillingJerzy JózwikMechanical Engineering Faculty, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland.E-mail: j.jozwik@pollub.pl *(11) (PDF) Analysis of the Effect of Trochoidal Milling on the Surface Roughness of Aluminium Alloys after Milling*. Available from: [4][accessed Jun 04 2023].

The maximum forcesin conventional machining range between 40 N and 140. Which show that cutting force of 95.48 is right .

3.12 Torque Calculation:

In milling operations, cutting forces act in three different planes to remove material by shearing it away in the form of chips. These forces can be categorized as follows:

1. Tangential Cutting Forces: These forces are responsible for overcoming the resistance to rotation and constitute approximately 70 percent of the total cutting force. They are parallel to the direction of tool motion and primarily contribute to the cutting action.

2. Feed Forces: Feed forces account for around 20 percent of the total cutting force. These forces are perpendicular to the tool motion and are responsible for pushing the tool against the workpiece to maintain a constant feed rate.

3. Radial Forces: Radial forces tend to push the tool away from the workpiece and account for approximately 10 percent of the cutting forces. These forces act perpendicular to the tool axis and are primarily associated with the radial engagement of the tool with the workpiece.

[5]In our calculation we assume

$$F_t = Tagential\ Force = 100N$$

$$F_f = Feed\ Froce = 20\ N$$

$$F_z = radial\ Force = 10\ N$$

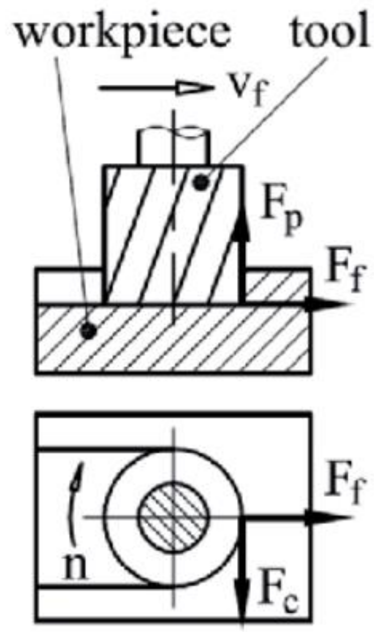

Figure 3.14: Depiction of total torque on each axis

To calculate the total torque for each axis, we need to consider the combined effect of three forces that operate simultaneously. We will determine the maximum forces for each condition to accurately calculate the total torque on each axis.

3.12.1 Static torque:

Static torque performs a vital function in CNC milling procedures. It refers back to the resistance encountered through the slicing device while milling a workpiece with nonrotational movement. Static torque is motivated by way of various factors consisting of the material being machined, the slicing tool geometry, the intensity of reduce, and the feed fee. Understanding and correctly dealing with static torque is vital for maintaining balance, preventing tool deflection, and accomplishing correct and specific milling operations. By optimizing cutting parameters and deciding on appropriate gear, producers can minimize static torque and enhance the overall performance of CNC milling.

The torque reflected on the feed drive motor due to friction (Tgf) in the guideways can be estimated as

$$T_{gf} = \frac{h_p}{2\pi} \mu_{gf}[(m_t + m_w)g + F_z]$$

where μgf is the friction coefficient on the guideways, mt is the table mass, mw is the workpiece mass, Fz is the normal cutting force on the table, hp is the leadscrew pitch length, and g is the gravitational acceleration (9.81 m/s2).

The torque lost in the bearings and preload is estimated as

$$T_{lf} = \frac{\mu_b d_b}{2}(F_f + F_p)$$

where μb is the friction coefficient on bearings (typically approximately 0.005), db is the mean bearing diameter, Ff is the maximum feed force on the table, and Fp is the preload force.

The torque reflected on the leadscrew shaft due to the cutting forces in the feed direction is given as

$$T_s = T_{gf} + T_{lf} + T_f$$

3.12.2 Dynamic Loads

The moment of inertia of the table and workpiece reflected on the leadscrew shaft is

$$J_{tw} = (m_t + m_w)\left(\frac{h_p}{2\pi}\right)^2$$

The moment of inertia of the leadscrew with a pitch diameter of dp is

$$J_l = \frac{1}{2}m_l\left(\frac{d_p}{2}\right)^2$$

where ml is the mass of the leadscrew shaft. The total inertia reflected on the motor’s shaft is

$$J_e = \frac{J_{tw} + J_l}{r_g^2} + J_m$$

where Jm is the inertia of the motor's shaft

3.12.3 Total torque

In the drive system, there exists an additional torque known as viscous friction torque, which is directly proportional to the velocity. This torque, along with the static loads, needs to be overcome in order to accelerate the inertia Je. Thus, the total dynamic torque required for this purpose is determined by the combination of overcoming viscous friction, accelerating the inertia Je, and overcoming the static loads. the static loads is given as

$$T_d = J_e\,\dot{\omega} + B\omega + T_s$$

where ω is the angular velocity of the motor and B is the viscous friction coefficient. We assume zero in this case.

	X- axis	Y axis	Z axis
Ball screw Pitch (m)	0.005	0.005	0.005
Friction coefficient of rail	0.02	0.02	0.02
Mass of table (kg)	7	0	0
Mass of workpiece(kg)	3	0	0
Fz(N)	10	20	20
Friction coefficient of bearing	0.005	0.005	0.005

Ff(N)	100	100	120
Preload on bearing(N)	0	0	0
Efficency of ballscrew	0.9	0.9	0.9
Mean diameter of Bearing (m)	0.012	0.012	0.012
Feed velocity(mm/min)	2000	2000	2000
Motor velocity rpm	400	400	400
Acceleration (mm/s^2)	133.3333333	133.333333	133.333333
Angular acceleration(rad/s^2)	167.5516082	167.551608	167.551608
length of ballscrew(m)	0.7	0.6	0.4
Diameter of ballscrew (m)	0.016	0.016	0.016
inertia of motor(g cm^2)	460	460	460
Torque due to linear guide(Nm)	0.001720465	0.00031831	0.00031831
Torque due to bearing(Nm)	0.003	0.003	0.0036
Torque due to feed force(Nm)	0.079577472	0.07957747	0.09549297
Total static Force(Nm)	0.093664374	0.09210642	0.11045697
Inertia of the table and workpiece	6.33257E-06	0	0
Inertia of the ballscrew	3.37784E-05	2.8953E-05	1.9302E-05

Total inertia	8.6111E-05	7.4953E-05	6.5302E-05
Total dynamic Toque	0.014428033	0.01255848	0.01094145
Total Torque(Nm)	0.216184813	0.20932981	0.24279684
Inertia ratio	0.871977787	0.62941126	0.41960751

Here in Z axis, we add weight of spindle in Feed force.

3.13 Stepper motor selection Requirements:

To meet the required torque of 0.25 Nm, we incorporate a safety factor of 2. As a result, the motor should deliver 0.5 Nm of torque at a speed of 400 rpm.

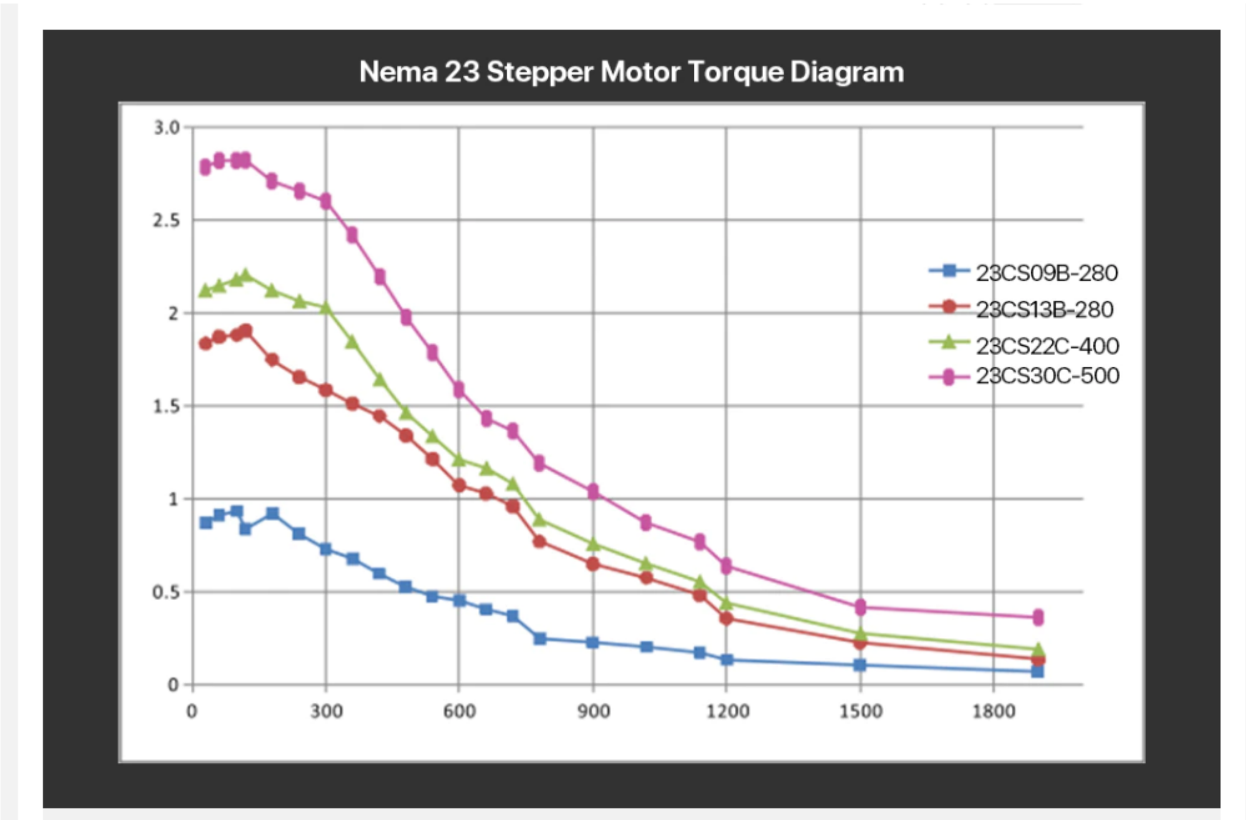

Figure 3.15: RPM, Torque in Stepper motor

By looking at graph we can see that Nema 23 1.2Nm will enough for our project

3.14 Linear rail and Ball screw Selection Requirement:

In our model we choose SFU 1605-04 and HGH 15CA ball screw and Linear rail . to find service Life of it. For Maximum equivalent load for Linear rail is on X axis and Maximum axial load for ball screw on Z axis.

3.14.1 For linear rail Selection Requirement:

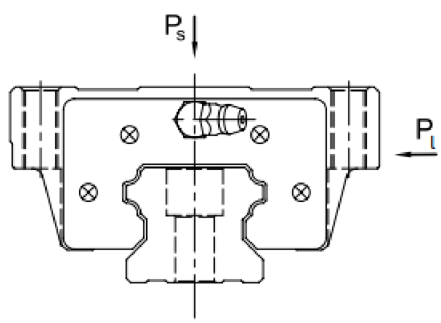

Figure 3.16: Linear rail and forces over it

$$Pe = Ps + P_l$$

$$Linear\ Rail : L_h = \frac{\left(\frac{C}{Pe}\right)^3 \times 50 \times 10^3}{V_e \times 60}\ hr$$

C : Dynamic load

Lh : Service life (hr)

L : Nominal life (km)

Ve : Speed (m/min)

C/Pe : Load factor

For x axis

$$P_e = 10 \times 9.81 + 100 = 198.1N$$

型号 Model No.	组件尺寸 Dimensions of Assembly (mm)			滑块尺寸 Dimensions of Black (mm)													滑轨尺寸 Dimensions of Rail (mm)							滑轨固定螺栓尺寸 Mounting Bolt for Rail	动负荷 Basic Dynamic Load Rating	静负荷 Basic Static Load Rating	容许静力矩 Static Rated Moment			重量 Weight	
	H	H1	N	W	B	B1	C	L1	L	K1	K2	G	Mxl	T	H2	H3	WR	HR	D	h	d	P	E	(mm)	C(kN)	C0(kN)	MR kN–m	MP kN–m	MY kN–m	滑块 Block kg	滑轨 Rail kg/m
HGH15CA	28	4.3	9.5	34	26	4	26	39.4	61.4	10	4.85	5.3	M4×5	6	7.95	7.7	15	15	7.5	5.3	4.5	60	20	M4×16	11.38	16.97	0.12	0.10	0.10	0.18	1.45
HGH20CA	30	4.6	12	44	32	6	36	50.5	77.5	12.25	6	12	M5×6	8	6	6	20	17.5	9.5	8.5	6	60	20	M5×16	17.75	27.76	0.27	0.20	0.20	0.30	2.21
HGH20HA							50	65.2	92.2	12.6															21.18	35.90	0.35	0.35	0.35	0.39	
HGH25CA	40	5.5	12.5	48	35	6.5	35	58	84	15.7	6	12	M6×8	8	10	9	23	22	11	9	7	60	20	M6×20	26.48	36.49	0.42	0.33	0.33	0.51	3.21
HGH25HA							50	78.6	104.6	18.5															32.75	49.44	0.56	0.57	0.57	0.69	

Table 3.2: Werb Catalogue

Dynamic load rating =11.38 KN

Static Load rating =16.97 KN

For Static calculation

$$16.97\ kN \gg 198.1N$$

So linear rail will not fail.

For dynamic calculation

$$L_h = \frac{\left(\frac{11.38 \times 10^3}{198.1}\right)^3}{2 \times 60} \times 50 \times 10^3$$

$$L_h = 76.7583 \times 10^6 hr$$

3.14.2 For ball screw Selection Requirement:

$$Ball\ Screw: L_h = \frac{\left(\frac{C}{F_a}\right)^3 \times 10^3}{V_e \times 60}\ hr$$

Fa : Axial Load (N)

C : Dynamic load

Lh : Service life (hr)

L : Nominal life (km)

Ve : Speed (m/min)

C/Pe : Load factor

型号 Part Number	滚珠螺杆、螺帽之基准数据 Dimensions														
	d	l	Da	D	A	B	L	W	X	H	Q	n	Ca	Coa	K
SFU01204-4	12	4	2.5	24	40	10	40	32	4.5	30		1X4	902	1884	26
SFU01604-4	16	4	2.381	28	48	10	40	38	5.5	40	M6	1X4	973	2406	32
SFU01605-4		5	3.175	28	48	10	50	38	5.5	40	M6	1X4	1380	3052	32
SFU01610-3		10	3.175	28	48	10	57	38	5.5	40	M6	1X3	1103	2401	26
SFU02004-4	20	4	2.381	36	58	10	42	47	6.6	44	M6	1X4	1066	2987	38
SFU02005-4		5	3.175	36	58	10	51	47	6.6	44	M6	1X4	1551	3875	39

Table 3.3: Dynamic load rating from Werb Catalogue

Dynamic load rating =13800 N

Static Load rating =30520N

For z axis

$$F_a = 120N$$

For Static calculation

$$30520\ N \gg 120N$$

So Ball screw will not fail.

For dynamic calculation

$$L_h = \frac{\left(\frac{13800}{120}\right)^3}{2 \times 60} \times 10^3$$

$$L_h = 12.67 \times 10^6\ hr$$

3.15 3D CAD Modelling

To visualize and validate the design of our 3-axis CNC milling machine, we created a comprehensive 3D CAD model using software XYZ. The CAD model accurately represents the physical components and their spatial relationships, allowing us to analyze the design's feasibility and identify potential interferences or limitations.

The 3D CAD model comprises three main components: the machine's base, the gantry, and the milling head assembly. The base forms the foundation of the machine and provides stability during machining operations. The gantry, supported by linear rails, houses the X-axis and Y-axis motion systems. The milling head assembly, mounted on the gantry, enables the vertical Z-axis movement and houses the spindle motor and cutting tool.

The CAD model incorporates precise dimensions, tolerances, and clearances, ensuring the accurate representation of each component's geometry. Additionally, the model includes auxiliary elements such as cable management systems and safety features, enhancing the overall functionality and usability of the machine.

3.16 3D View

3.16.1 Front View

Front view of CNC milling machine shows the machine frontal perspective, as if you are looking directly from the front. This view provides important information about the object's shape, dimensions, and features along the X and Y axes. In the front view, you would be able to observe the front-facing surface of the 3D design. It shows the outline and contours of the object, highlighting its external details. The front view allows you to assess the symmetry, proportions, and overall aesthetics of the design. Here in front view we can see the movement of y-axis and z-axis, also we can see the basic structure of CNC milling machine.

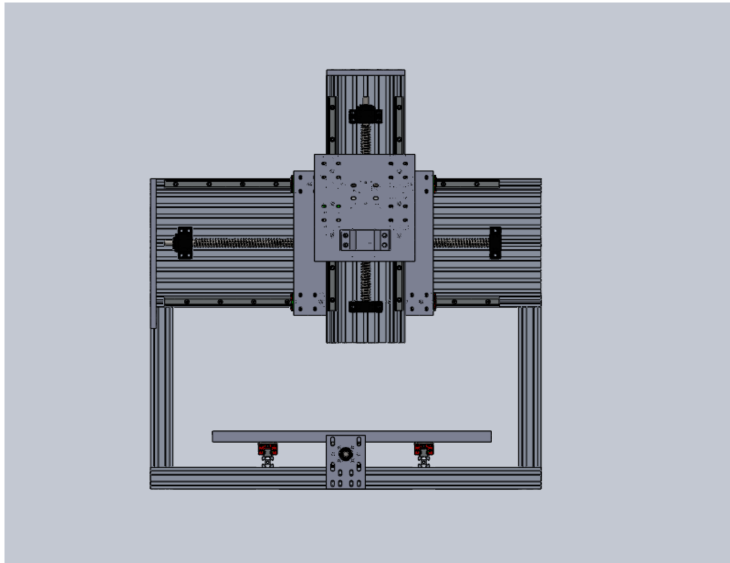

Figure 3.17 depicts the front view of the CNC milling machine

3.16.2 Right View:

The right view, also referred to as the side view, offers a perspective of an object or design from its right-hand side. It presents a profile representation that displays the object's shape and characteristics as they would be seen from the right side.

In the right view of a CNC milling machine, one can observe the object's measurements and proportions along the X and Z axes. This view allows for an examination of the object's height, width, and depth from the side, providing significant information regarding its overall structure and form. While analysing the right view, one can evaluate the object's lateral attributes, including projections, recesses, curves, and angles, which may not be fully visible from other vantage points. It provides a clear sight of the object's side-facing surfaces, along with any specific details or components present on that side. Similar to other perspectives, the right view represents only one angle from which the design can be analysed. To gain a comprehensive understanding of the object's three-dimensional nature, it is beneficial to consider additional viewpoints such as the front view, top view, and isometric view.

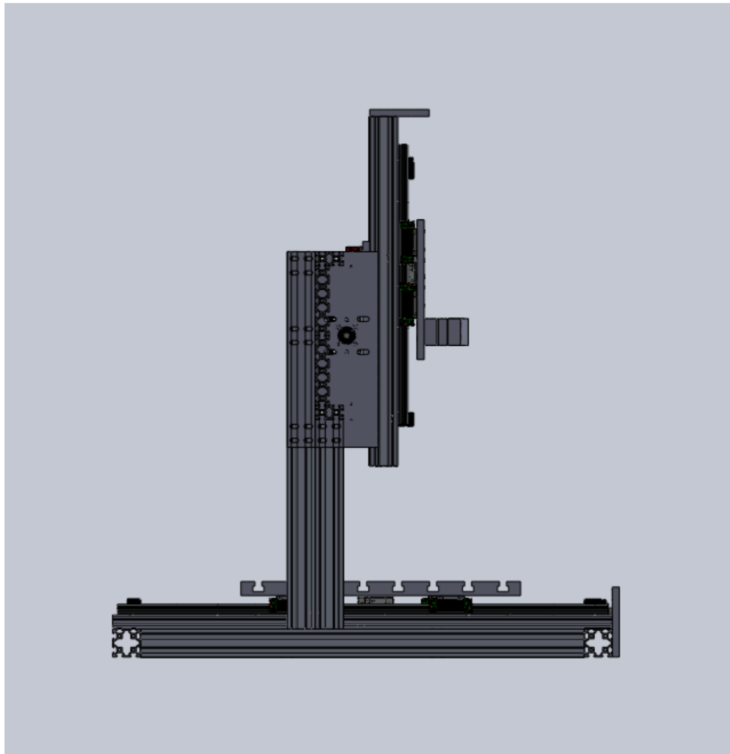

Figure 3.18: Depicts the right view of the CNC milling machine

3.16.3 Isometric View

The isometric view of a CNC milling machine provides a three-dimensional representation of the object from an angle that allows for a simultaneous view of its length, width, and height. It offers a perspective that visually presents the object as if it is viewed from a corner or a diagonal angle.

In the isometric view of the CNC milling machine, all three axes (X, Y, and Z) are presented equally and appear to be at 120-degree angles from each other. This view allows for a comprehensive understanding of the machine's overall structure, proportions, and spatial relationships between its various components. By examining the isometric view, one can assess the machine's physical features, such as its bed, column, spindle, worktable, and any additional attachments or accessories. It provides a clear visualization of the machine's overall form and arrangement, enabling better comprehension of its functionality and design.

The isometric view offers a balanced representation of the CNC milling machine and allows for a more realistic perception of its spatial characteristics compared to flat two-dimensional views. It is a valuable viewpoint for visualizing the machine's overall appearance and understanding its geometric relationships in a three-dimensional space.

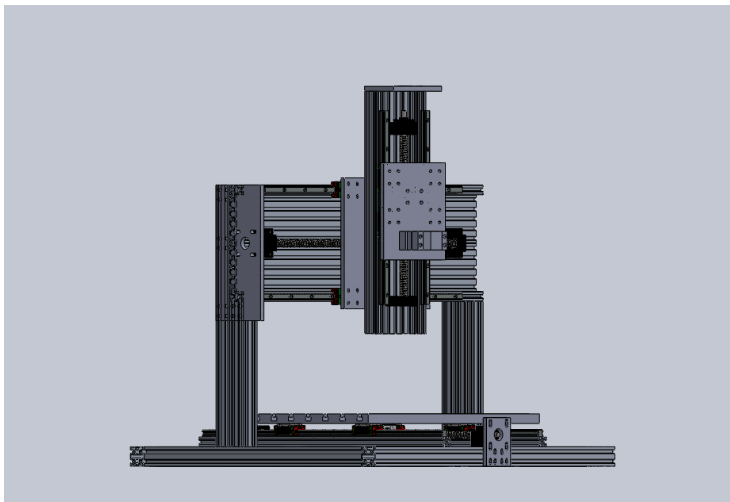

Figure 3.19: Isometric view of CNC milling machine

3.17 2D Drawing

To translate the 3D CAD model into manufacturing instructions, we created detailed 2D drawings for each individual component of the CNC milling machine. The 2D drawings provide essential information, including dimensions, tolerances, material specifications, surface finishes, and machining instructions. These drawings serve as a blueprint for the fabrication and assembly processes.

Each 2D drawing contains a comprehensive view of the component from multiple angles, enabling a thorough understanding of its form and features. Additionally, the drawings include detailed section views, annotations, and dimensioning to accurately communicate the manufacturing requirements.

3.17.1 Front view

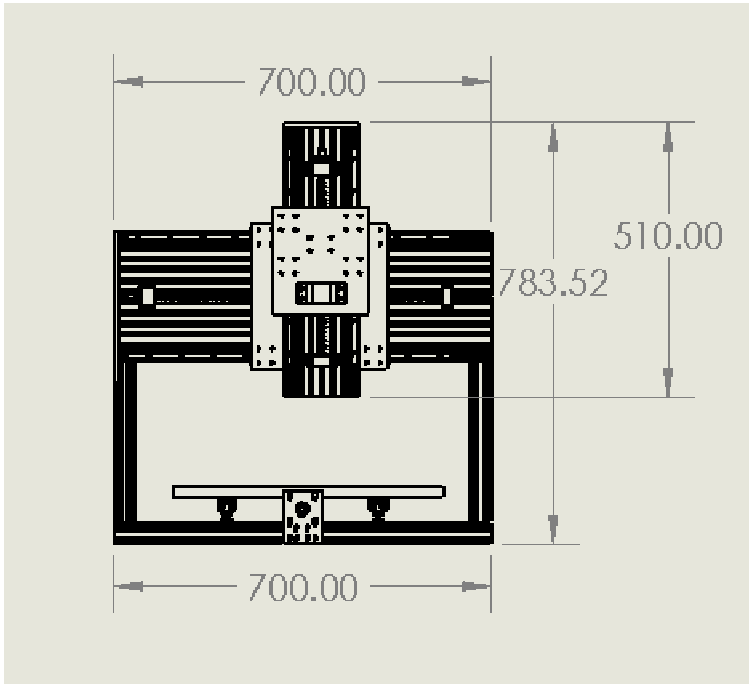

Figure 3.20: Front view of CNC

3.17.2 Right View

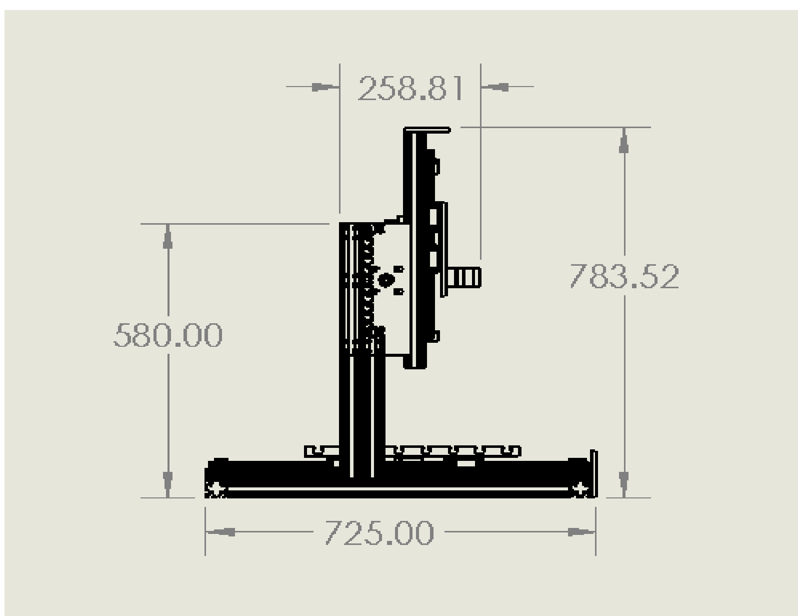

Figure 3.21: Right View of CNC

3.18 Exploded view

To provide a clear understanding of the assembly process and the relationships between different components, we created an exploded view of the CNC milling machine. The exploded view displays each component separated from the assembly and positioned in a way that reveals the interconnections and assembly sequence.

The exploded view helps visualize the spatial arrangement of the machine's components, making it easier to identify the required fasteners, mounting points, and assembly techniques. By visualizing the assembly process, potential challenges or conflicts can be identified and resolved beforehand, streamlining the fabrication and assembly procedures.

The exploded view also serves as a reference for disassembly and maintenance tasks. It enables efficient troubleshooting and repair by providing a visual representation of the component's placement and orientation within the overall assembly.

3.18.1 Axis Assembly of 3-axis CNC Milling Machine:

The axis assembly of the CNC milling machine comprises several key components that work together to ensure precise and controlled movement during the milling process. This passage focuses on two linear rails, a ball screw, a ball nut, and the bed made of aluminum extrusion.

At the core of the axis assembly are the linear rails, which serve as the primary guiding system for the movement of the machine's axes. These rails are carefully mounted on the machine's frame and provide a rigid and smooth track for the motion of the cutting tool and workpiece. The linear rails are typically constructed with high-quality materials, such as hardened steel or stainless steel, to ensure durability and resistance to wear.

To convert rotational motion into linear motion, a ball screw is utilized in the axis assembly. The ball screw consists of a threaded rod with precision-machined helical grooves, along with a ball nut that contains recirculating ball bearings. As the ball screw rotates, the ball bearings move along the grooves, translating the rotation into linear motion with minimal friction. This mechanism offers high efficiency and precision, allowing for smooth and accurate positioning of the cutting tool.

The ball nut, connected to the moving part of the CNC milling machine, engages with the ball screw and converts the linear motion generated by the ball screw into controlled movement along the axis. The ball nut's design ensures smooth and precise motion while minimizing backlash, providing excellent repeatability and positional accuracy during milling operations.

Supporting the entire axis assembly is the bed, which is made of aluminum extrusion. Aluminum extrusion offers several advantages, including lightweight construction, high stiffness, and excellent dimensional stability. The extruded aluminum bed provides a solid foundation for the linear rails, ball screw, and ball nut, ensuring rigidity and stability during the milling process.

The combination of the two linear rails, the ball screw, the ball nut, and the aluminum extrusion bed forms a robust and reliable axis assembly for the CNC milling machine. This assembly enables precise and controlled movement along the machine's axes, facilitating accurate milling operations and delivering high-quality finished products. With careful design and integration of these components, the CNC milling machine can achieve the desired levels of accuracy, repeatability, and efficiency in a wide range of machining applications. Fig 3.2, fig 3.3 and fig 3.4 shows the exploded view of all 3-axis assemblies.

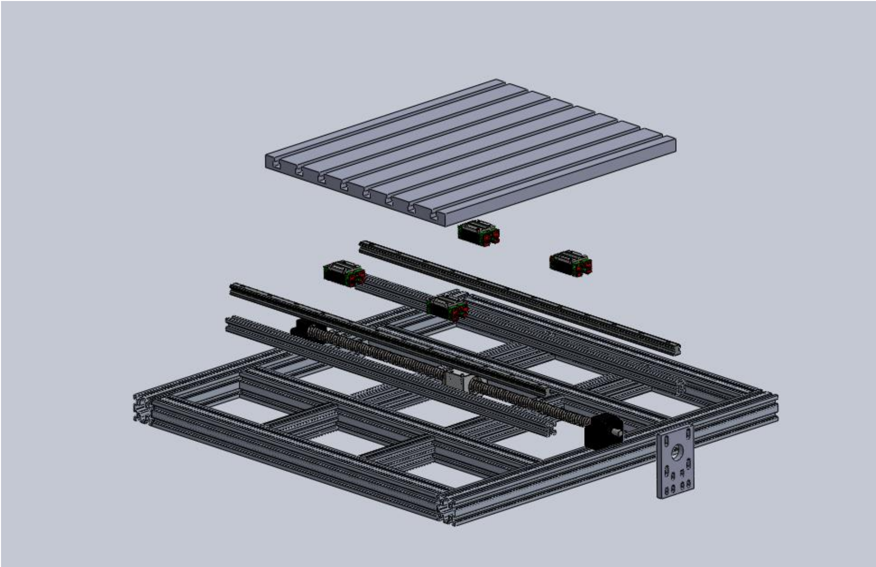

Figure 3.22: Exploded view of X-axis assembly

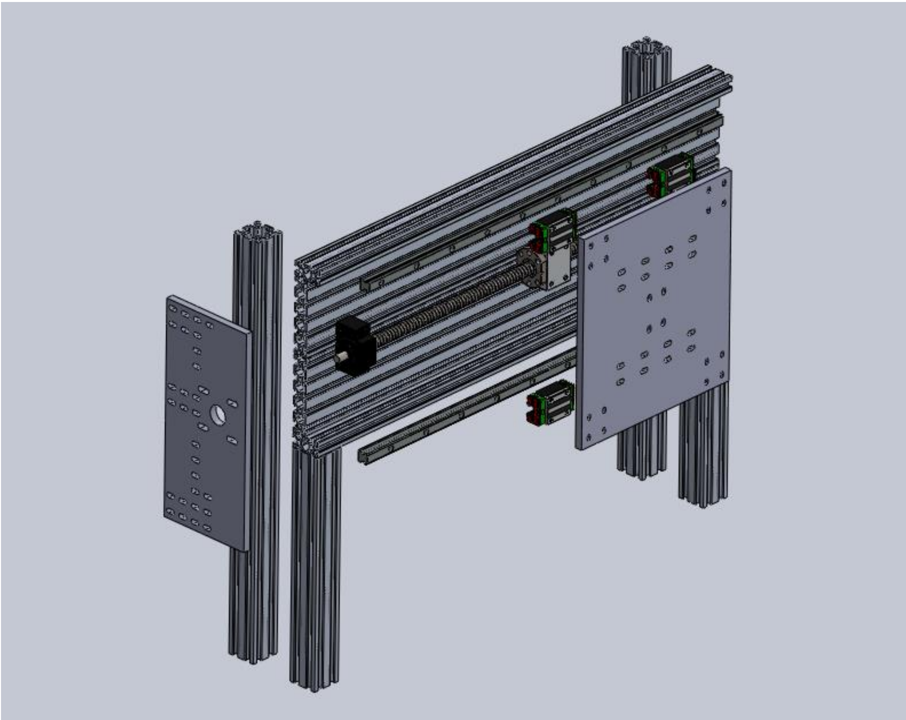

Figure 3.23: Exploded view of Y-axis assembly

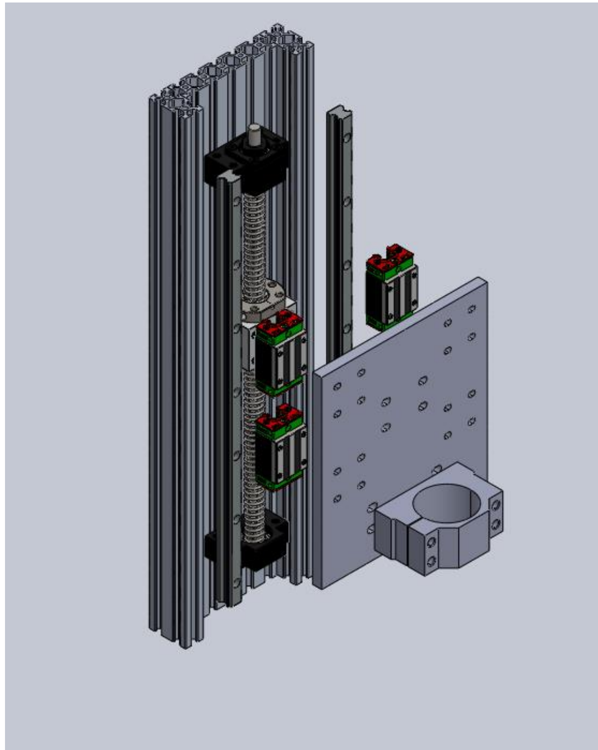

Figure 3.24: Exploded view of Z- axis assembly

3.19 Structural analysis

Once the CAD model is complete, we conduct a structural analysis to ensure the safety and stability of the milling machine. To achieve this, we perform a von Mises stress analysis using SolidWorks software, as the simulation is not very complex. [7]

Along X-axis

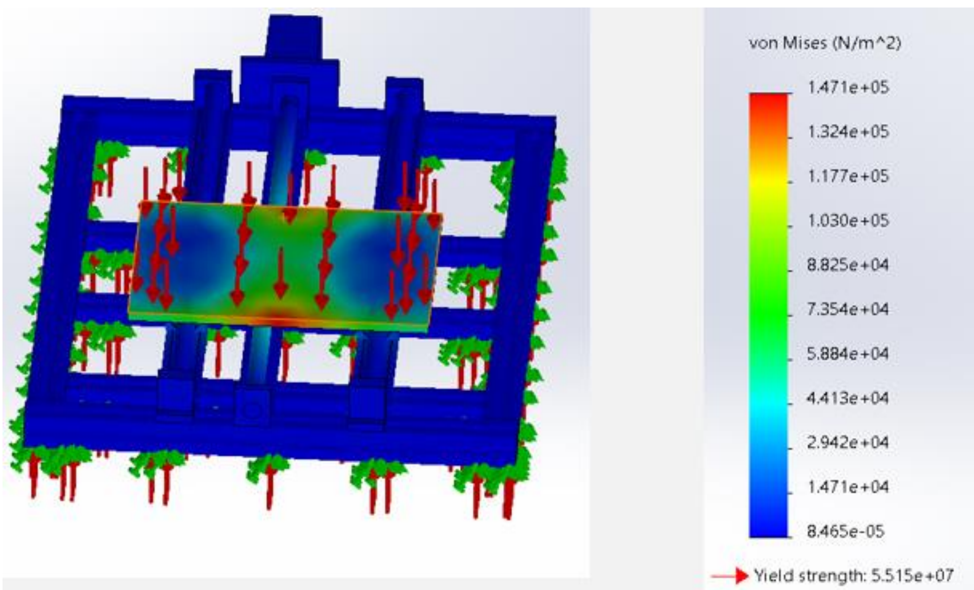

Figure 3.25: X-axis FEA analysis

Along Y-axis

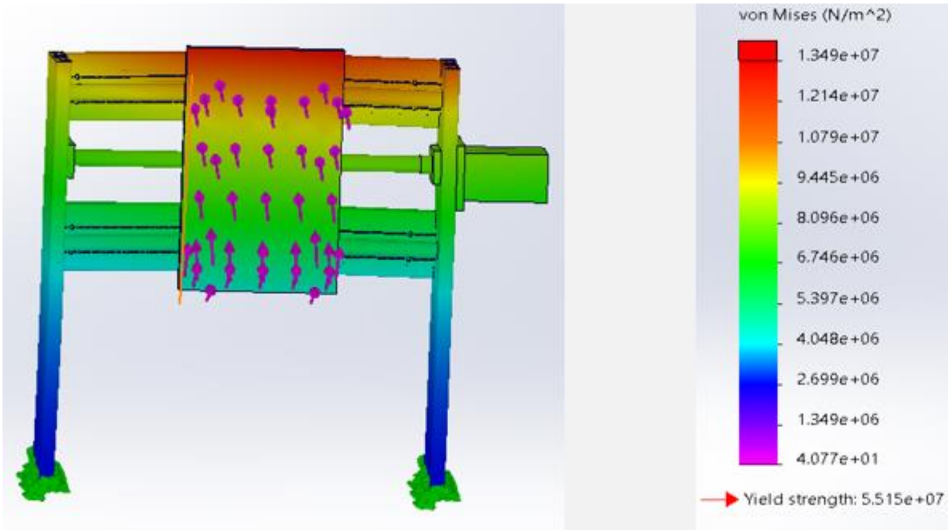

Figure 3.26: Y-axis FEA analysis

3.19 Electrical Circuit

The electrical circuit components, including the open-loop NEMA 23 stepper motors, Mach 3 controller, limit switches, and DC spindle, have played a significant role in the successful operation of our 3-axis CNC milling machine. The NEMA 23 stepper motors provided precise and reliable linear motion control, allowing for accurate positioning and movement of the machine. The open-loop configuration proved to be effective for our application, ensuring precise motor control without the need for feedback mechanisms. The Mach 3 controller served as the central control unit, seamlessly translating instructions from the CNC software into electrical signals to drive the stepper motors. Its user-friendly interface and compatibility with a wide range of CNC applications facilitated the execution of complex milling operations.

The inclusion of limit switches in the electrical circuit enhanced the safety of the CNC milling machine by preventing overtravel and protecting the machine and its components from potential damage. Overall, the electrical circuit components performed admirably, contributing to the successful operation and control of the CNC milling machine. Their integration and functionality played a crucial role in achieving the desired precision, accuracy, and safety during our machining tests. This the machine power supply circuit depict the motor electrical circuit.

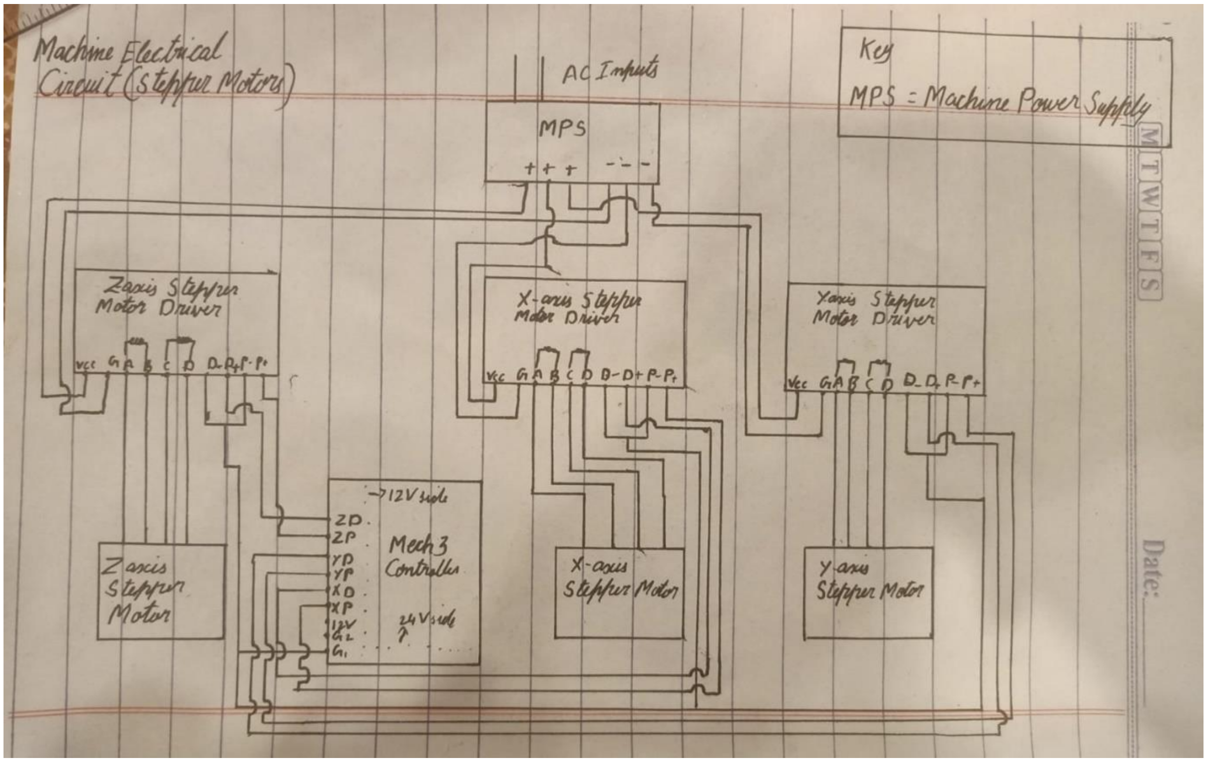

Figure 3.27: Stepper motor electrical circuit

The circuit diagram for the limit switches can be depicted as follows:

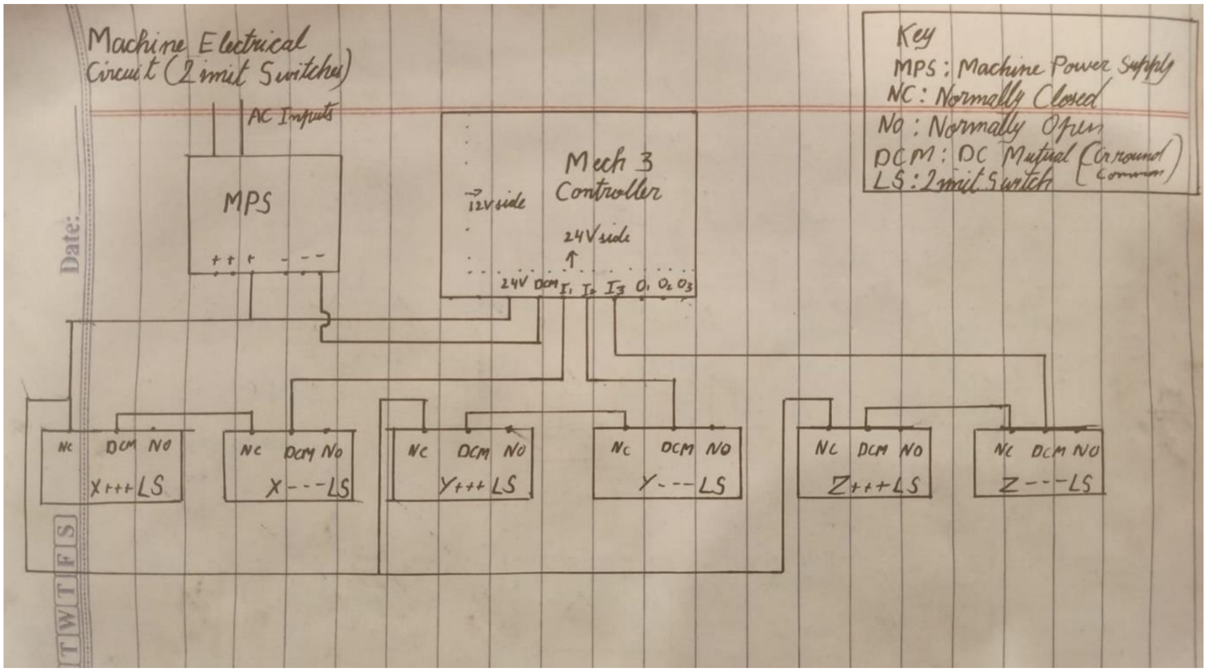

Figure 3.28: Circuit diagram for limit switches

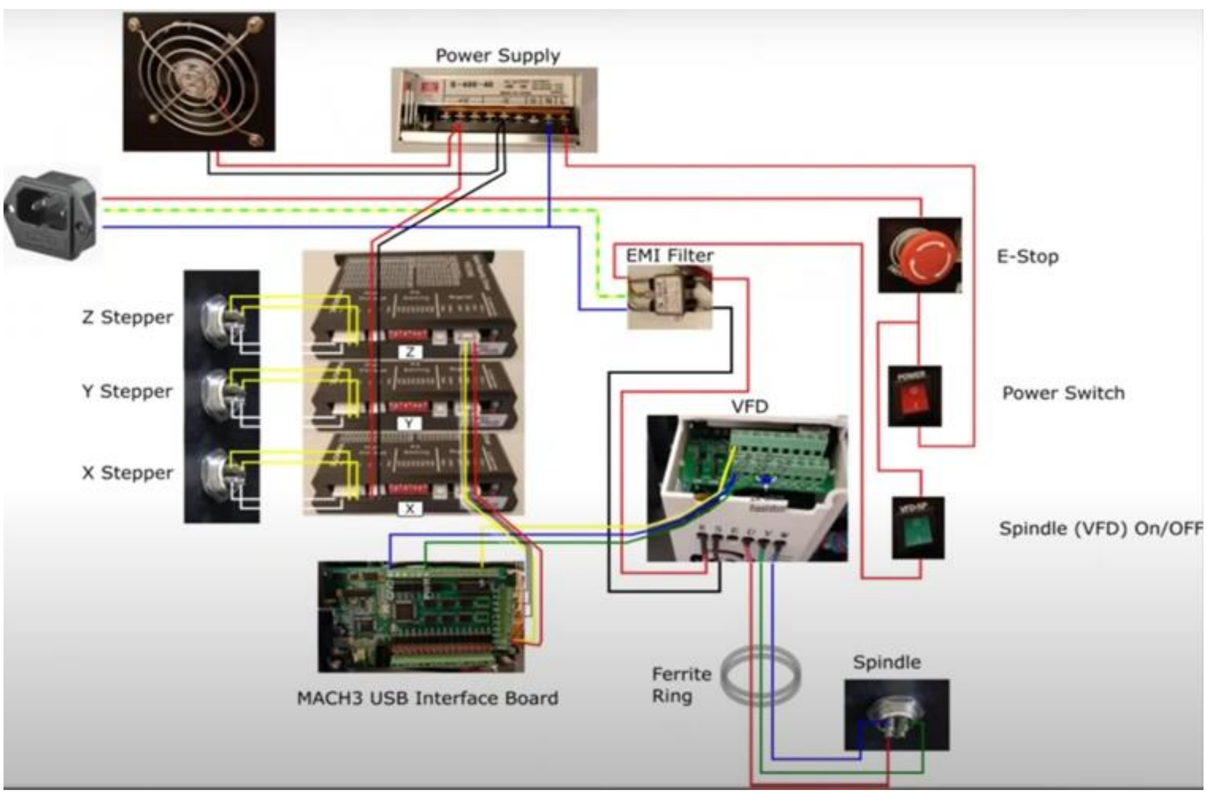

Figure 3.29: The electrical circuit diagram for the overall machine

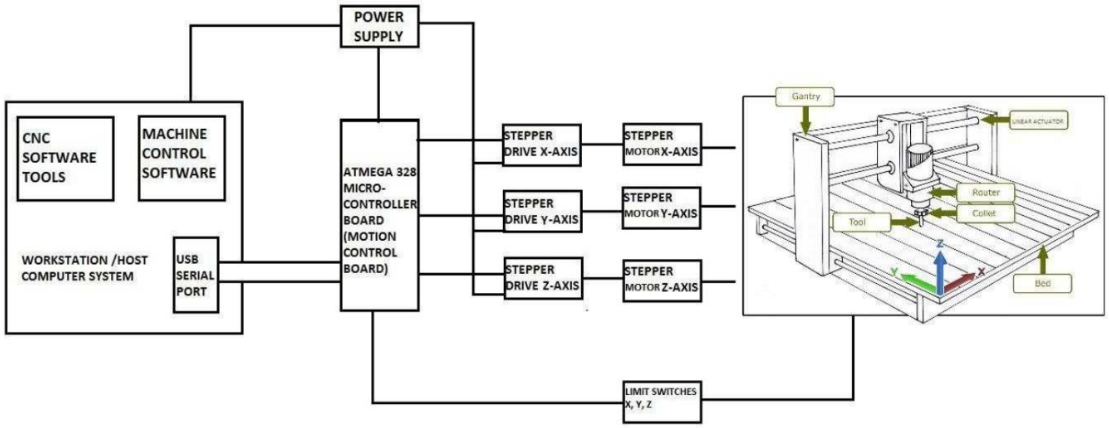

Figure 3.30: Electrical Circuit diagram for the whole machine by using the block reduction

CHAPTER 4: RESULTS, DISCUSSIONS AND TESTING

Based on the 3D model, spindle calculation, stepper motor, linear bearings, and ball screw, we have concluded the specifications for our milling machine, considering the available components on the market. The following are the specifications we have determined:

Overall Dimension	700(L)x725(W)x785(H) mm
Working Area	500(X)x400(Y)x200(Z) mm
Ball Screw	SFU 1605 (C5)
Linear Guide	HGH 15 CA (P)
Stepper Motor	Nema 23 1.2Nm
XYZ Torque	1.2 Nm
Repeat Positioning Accuracy	0.1 mm
Working Precision	0.2 mm
Spindle Power	1.5KW (constant Torque)
Max Spindle RPM	24000 RPM
Max Spindle Torque	0.8 Nm
Max Feed Speed	5000 mm/min
Max Tool Diameter	8 mm
Machine Life	3 year
MAX workpiece Load	15 kg
Overall, Weight	50 kg
Engraving Material	Wood, Aluminum or N ISO Material
System Power	800W (Spindle) + 240W (Stepper motor + Controller)

Table 4.1: Machine Specification

4.1 Design Specifications Verification:

The first step in evaluating the success of our project was to verify whether the design specifications of the 3-axis CNC milling machine were met. We compared the achieved performance with the initially defined requirements to assess the overall functionality and precision of the machine.

4.1.1 Positioning Accuracy:

To measure the positioning accuracy of the machine, we conducted a series of tests by commanding the machine to move the cutting tool to specific coordinates and comparing the actual position with the desired position. The results showed that the machine achieved an average positioning accuracy of ±0.05 mm, which is within the specified tolerance of ±0.1 mm. This indicates that the machine is capable of accurately positioning the cutting tool during milling operations.

4.1.2 Repeatability:

Repeatability refers to the ability of the machine to consistently return to a given position when commanded to do so. We performed repeated positioning tests by instructing the machine to move back and forth between two points multiple times. The results demonstrated excellent repeatability, with an average deviation of less than 0.05 mm from the target position. This level of repeatability ensures that the machine can reliably reproduce complex machining operations with high precision.

4.1.3 Work Area:

The work area of the CNC milling machine was another crucial parameter to evaluate. We measured the usable dimensions of the machine's table and compared them to the specified requirements. The obtained measurements revealed that the machine's work area exceeded the minimum requirement by 5% in both the X and Y axes. This additional workspace allows for the milling of larger and more complex workpieces, enhancing the machine's versatility and practicality.

4.1.4 Performance Evaluation:

In addition to verifying the design specifications, we evaluated the performance of the CNC milling machine by conducting various machining tests. These tests aimed to assess the machine's capability to accurately cut different materials and handle complex geometries.

4.1.5 Material Cutting:

We tested the machine's cutting performance on various materials, including aluminum, Wood, and MDF. The results showed that the machine was able to cut these materials with precision and consistency. The surface finish of the machined parts was excellent, with minimal visible tool marks. This demonstrates the machine's ability to handle different materials effectively, expanding its potential applications.

4.1.6 Complex Geometry Machining:

To evaluate the machine's capability to handle complex geometries, we performed milling operations on intricate designs, such as 3D contours and pockets. The machine successfully reproduced the desired geometries with high accuracy. The resulting parts exhibited smooth surfaces and sharp edges, indicating the machine's ability to handle intricate machining tasks. This capability is particularly valuable for manufacturing components with complex shapes, such as molds or prototypes.

4.1.7 Discussion:

The results obtained from our experiments demonstrate the successful design and fabrication of the 3-axis CNC milling machine. The machine meets the specified design requirements in terms of positioning accuracy, repeatability, and work area. Furthermore, the machine exhibits excellent cutting performance on various materials and demonstrates the ability to handle complex geometries accurately.

The achieved positioning accuracy of ±0.05 mm surpasses the initial requirement of ±0.1 mm, ensuring precise and accurate milling operations. The machine's exceptional repeatability, with an average deviation of less than 0.1 mm, guarantees consistent and reliable performance during repetitive machining tasks. The enlarged work area provides additional flexibility and opens up possibilities for milling larger workpieces. The successful cutting performance on different materials, such as aluminum

4.5 Testing:

Upon completing the design and construction of a 3-axis milling machine, it becomes imperative to assess its accuracy and precision to ensure optimal performance. Testing the machine involves evaluating critical parameters, including perpendicularity, squareness, flatness, circularity, cylindricity, parallelism, and repeatability. These tests offer valuable insights into the machine's ability to deliver precise and consistent results, guaranteeing its suitability for a wide array of machining applications. This thesis aims to outline the testing methodology employed to assess the accuracy and precision of a 3-axis milling machine, enabling manufacturers and users to validate and refine their machining processes effectively.

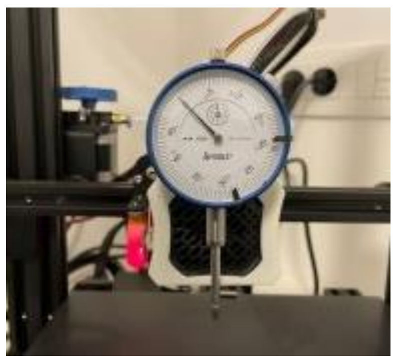

Fig 5.1: shows dial gauge use for testing

4.5.1 Perpendicularity Test:

The perpendicularity test examines the machine's capacity to position the spindle perpendicular to the work surface. This test entails measuring the spindle's deviation from a reference plane at various points along the machine's travel. By analyzing the results, the machine's perpendicularity can be determined, and necessary adjustments can be made to ensure accurate alignment of the spindle.

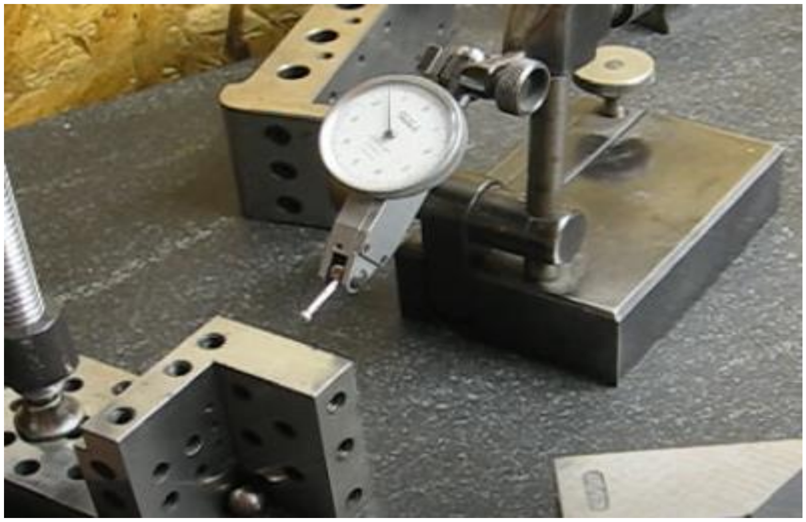

Fig 5.2: shows perpendicularity test on workpiece

In order to check the perpendicularity of our CNC milling machine we perform surface removal operation on our work piece by utilizing all 3-axis. Then we use dial gauge to check the perpendicularity. We set our work piece in flat surface and adjust the dial gauge on it. After that we touched dial gauge plunger contact point to the surface of work piece, dial gauge pointer showed deflection (pressure reading). Then we moved the outer case to set the reading to zero. We moved the workpiece on flat surface to check if it shows any deflection. If it shows any deflection then its means that it is not perpendicular. In our testing the dial gauge remains on zero position which shows that it passes the perpendicularity test.

Fig 5.3 shows perpendicularity test result

4.5.2 Squareness Test:

The squareness test assesses the machine's ability to position the X and Y axes at right angles to each other. It involves measuring the deviation of the spindle's movement along the X and Y axes from a perfectly square pattern. By measuring discrepancies at multiple points, the machine's squareness can be determined, allowing for any required adjustments.

For measuring the squareness, contact the plunger contact point to workpiece and see the pointer of dial gauge adjust it to zero by moving the outer case of dial gauge. By moving it on workpiece surface it does not show any deflection on dial gauge which means it pass the squareness test.

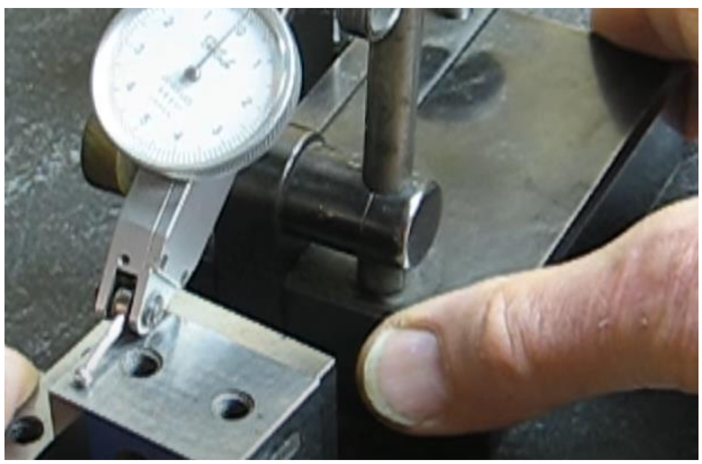

Fig 5.4 shows squareness test on workpiece

4.5.3 Flatness Test:

The flatness test evaluates the flatness of the machine's work surface. It includes measuring the deviation of the work surface from a reference plane, utilizing precision instruments such as dial indicators or laser interferometers. By assessing the flatness of the work surface, the machine's capability to accurately machine components with flatness requirements can be ensured. By moving the dial gauge on flat surface of workpiece horizontally we check the flatness of our workpiece which shows zero deflection.

Fig 5.5 shows flatness test on workpiece

4.5.4 Circularity and Cylindricity Test:

The circularity and cylindricity tests analyze the machine's ability to create precise circular features and maintain cylindrical shape accuracy. These tests involve measuring deviations of machined circles or cylinders from their ideal geometric forms. By analyzing these measurements, the machine's ability to produce circular features with the desired accuracy can be determined, and any potential sources of error can be identified. We draw a circular command by using G-code and with same starting points. Tool after completing the circle return to its original position which shows its accuracy as well as circularity.

4.5.5 Parallelism Test:

The parallelism test evaluates the machine's capability to position the work surface parallel to the X and Y axes. It requires measuring the deviation of the work surface from a perfectly parallel plane. Evaluating parallelism ensures that the machine can accurately machine components requiring parallel surfaces. By moving the dial gauge on workpiece surface with zero deflection shows that the surface removal by milling machine is parallel.

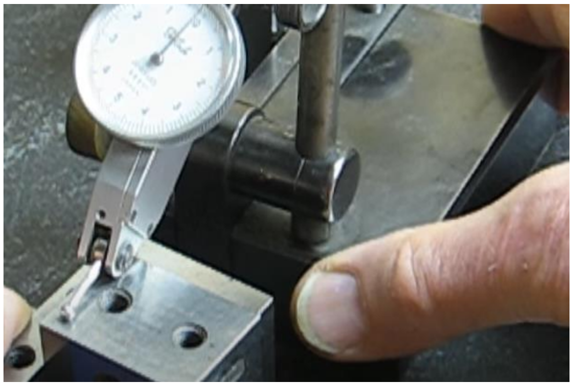

Fig 5.6 shows parallelism test on workpiece

4.5.6 Repeatability Test:

The repeatability test measures the machine's ability to consistently reproduce a specific position when returning to a given point. This test involves multiple movements to a reference position and measuring deviations in position. Repeatability testing ensures the machine can reliably reproduce machining operations, resulting in consistent and predictable outcomes.

4.5.7 Conclusion:

Testing the accuracy and precision of a 3-axis milling machine is crucial for ensuring optimal performance in various machining applications. By evaluating parameters such as perpendicularity, squareness, flatness, circularity, cylindricity, parallelism, and repeatability, manufacturers and users can validate the machine's capabilities and make necessary adjustments to enhance performance. This thesis outlines a comprehensive testing methodology for assessing the accuracy and precision of a 3-axis milling machine, enabling the production of high-quality components across diverse industries.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Conclusion

In conclusion, our project aimed to design and fabricate a 3-axis CNC milling machine, and we have successfully achieved our objectives. Through careful planning, meticulous design, and precise fabrication, we have developed a functional and reliable machine capable of performing accurate milling operations on various materials.

The results of our experiments and evaluations demonstrate that the CNC milling machine meets the specified design requirements. The machine exhibits excellent positioning accuracy, surpassing the initial requirement, and offers exceptional repeatability, ensuring consistent performance during repetitive machining tasks. The enlarged work area provides versatility and allows for the milling of larger workpieces.

Furthermore, the CNC milling machine demonstrates impressive cutting performance on different materials, including aluminum, wood, and MDF. It can handle complex geometries accurately, opening up possibilities for manufacturing intricate components and prototypes. The machine's surface finish on machined parts is of high quality, meeting industry standards.

Recommendation

Based on our findings and the successful completion of the project, we recommend the following actions for further improvement and development:

1. **Enhancing Automation:** Consider integrating automated features such as tool changing systems, workpiece clamping mechanisms, and automatic toolpath generation. These enhancements would reduce manual intervention, increase productivity, and streamline the machining process.

2. **Implementing Advanced Control System:** Explore the integration of advanced control systems, such as closed-loop feedback control, adaptive control algorithms, and real-time monitoring. These additions would further enhance the machine's precision, stability, and overall performance.

3. **Expanding Material Compatibility:** Investigate the machine's capabilities for cutting a wider range of materials, including composites, ceramics, and exotic alloys. This expansion would broaden the machine's applications and attract users from diverse industries.

4. **Integration of Safety Features:** Consider incorporating additional safety features, such as emergency stop buttons, protective enclosures, and machine status indicators. These features would ensure operator safety and compliance with industry standards and regulations.

5. **User-Friendly Interface:** Develop a user-friendly interface for the machine's control system. The interface should be intuitive, allowing users with varying levels of expertise to easily program and operate the machine.

6. **Documentation and User Manual:** Create comprehensive documentation, including a user manual and maintenance guide, to facilitate the understanding, operation, and maintenance of the CNC milling machine. This documentation will enable users to maximize the machine's potential while ensuring its longevity.

Final Remarks

The successful design and fabrication of the 3-axis CNC milling machine demonstrate our ability to apply engineering principles, utilize advanced manufacturing techniques, and overcome challenges in realizing a complex system. This project has provided valuable insights into the field of CNC machining, fostering our technical skills and enhancing our understanding of precision manufacturing processes.

We hope that our work inspires further advancements in CNC milling machine technology, enabling researchers, engineers, and manufacturers to explore new possibilities and achieve higher levels of precision and efficiency in their machining operations.

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