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Design and fabrication of a 5-Axis CNC milling machine

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بسم الله الرحمن الرحيم

Dedication

I dedicate this work:

To myself, for never giving up.

To my parents, for their unconditional support.

To my siblings, for their encouragement.

To my family, for always being there.

To my friends, for the memories and support.

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Abstract

This thesis details the design, mechatronic integration, and software configuration of a low-cost 5-axis CNC milling machine prototype featuring a bi-rotary head. The work covers the mechanical assembly of the structural frame, the optimization of a strategically zoned electrical cabinet governed by an ST-V3 motion controller, and the digital configuration within Mach3. To enable simultaneous 5-axis trajectory generation, a custom SolidCAM post-processor was developed by modifying the machine's VMID and GPP files. Finally, a Business Model Canvas (BMC) framework is applied to evaluate the commercial viability and industrial potential of the prototype.

Keywords: 5-Axis CNC, Bi-rotary Head, Mechatronics, Mach3, SolidCAM, Post-processor.

Résumé

Cette thèse présente la conception, l'intégration mécatronique et la configuration logicielle d'un prototype de fraiseuse CNC 5 axes à bas coût avec une tête bi-rotative. Ce travail couvre l'assemblage mécanique du châssis, l'optimisation d'une armoire électrique zonée gérée par un contrôleur ST-V3, et la configuration sous Mach3. Pour permettre la génération de trajectoires 5 axes simultanées, un post-processeur SolidCAM personnalisé a été développé en modifiant les fichiers VMID et GPP de la machine. Enfin, le modèle de Business Model Canvas (BMC) est appliqué pour évaluer la viabilité commerciale et le potentiel industriel du prototype.

Mots-clés: CNC 5 axes, Tête bi-rotative, Mécatronique, Mach3, SolidCAM, Post-processeur.

الملخص

تفصل هذه المذكرة تصميم ، تجميع، والإعداد البرمجي لنموذج أولي لآلة تفريز ذات تحكم رقمي 5-Axis CNC منخفضة التكلفة برأس ثنائي الدوران. يشمل المشروع التطوير الميكانيكي للهيكل، وتصميم خزانة كهربائية محسنة ومدارة بوحدة التحكم ST-V3 ، بالإضافة إلى الإعداد الرقمي عبر برنامج Mach3 . ولتوليد مسارات حركة متزامنة، تم تطوير معالج بعدي مخصص على برنامج SolidCAM بتعديل ملفات VMID و GPP . أخيرًا، تم تقييم الجدوى التجارية والإمكانات الصناعية للنموذج الأولي باستخدام مخطط نموذج العمل التجاري (BMC) .

الكلمات المفتاحية: 5-Axis CNC ، رأس ثنائي الدوران، ميكاترونيك، Mach3 ، SolidCAM ، معالج بعدي.

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Abreviations list

Acronyme	Signification
ESSAT	École Supérieure en Sciences Appliquées.
NC	Numerical Control / Normally Closed.
CNC	Computer Numerical Control.
CAD	Computer-Aided Design.
CAM	Computer-Aided Manufacturing.
G-code	Geometric Code.
APT	Automatically Programmed Tool.
HMI	Human–Machine Interface.
PTP	Point-to-Point.
EDM	Electrical Discharge Machining.
BMC	Business Model Canvas.
PCB	Printed Circuit Board.
PID	Proportional–Integral–Derivative.
FDA	Food and Drug Administration.
ISO	International Organization for Standardization.
PWM	Pulse-Width Modulation.
PLC	Programmable Logic Controller.
NURBS	Non-Uniform Rational B-Spline.
VMID	Virtual Machine ID.
GPP	General Post-Processor.
BOB	Breakout Board.
LPT	Line Print Terminal (Parallel Port).
USB	Universal Serial Bus.
UGS	Universal Gcode Sender.
GRBL	G-code Real-time Bootloader (open-source firmware).
VFD	Variable Frequency Drive.
PMSM	Permanent Magnet Synchronous Motor.
DC	Direct Current.
AC	Alternating Current.
NO	Normally Open.
NPN	Negative-Positive-Negative (transistor type).
PNP	Positive-Negative-Positive (transistor type).
SPDT	Single Pole Double Throw.
SPST	Single Pole Single Throw.

Acronyme	Signification
HTD	High Torque Drive (belt profile).
DIY	Do It Yourself.
BLDC	Brushless DC (Direct Current) Motor.
EMI	Electromagnetic Interference.
RPM	Revolutions Per Minute.
DIN	Deutsches Institut für Normung (German Standards Rail).
AWG	American Wire Gauge.
TCPC	Tool Center Point Control.
GUI	Graphical User Interface.
IEC	International Electrotechnical Commission.

General Introduction

In recent years, manufacturing technologies have experienced rapid development driven by the rise of automation, digital control, and the growing demand for high precision. Among these advances, Computer Numerical Control (CNC) machines have become indispensable in modern industry because of their accuracy, repeatability, and versatility. They are widely used in aerospace, automotive, electronics, and prototyping sectors, where precision and efficiency are critical requirements.

Traditional 3-axis CNC machines, while common in educational and small-scale industrial environments, are limited in their capacity to produce complex parts or intricate geometries. The emergence of 5-axis CNC machines has addressed this limitation by enabling simultaneous motion along five different axes, allowing multi-sided machining in a single setup. This capability reduces repositioning errors, improves surface finish, and significantly enhances productivity.

However, despite their technical advantages, 5-axis CNC machines remain costly and complex to implement. Their price, programming difficulty, and maintenance requirements make them inaccessible for many small manufacturers, technical institutions, and independent innovators. This situation highlights the need for a low-cost, compact, modular 5-axis CNC prototype that can provide acceptable precision and performance while remaining affordable and adaptable to educational and prototyping contexts.

Project Overview

This project focuses on the design and fabrication of a 5-axis CNC milling machine prototype. The prototype integrates mechanical, electrical, and control subsystems to achieve coordinated motion across three translational axes (X, Y, Z) and two rotational axes (A, B). The work includes mechanical modeling, electronic integration, control configuration, and prototype testing. The ultimate goal is to develop a functional system that demonstrates the feasibility of an affordable, small-scale 5-axis CNC platform.

Problem Statement

Conventional 3-axis CNC machines cannot efficiently manufacture complex 3D parts or features that require multiple orientations, limiting productivity and accuracy. Meanwhile, existing 5-axis machines are often too expensive or technically demanding for educational or small-scale production use. This project aims to bridge that gap by creating an accessible prototype that combines multi-axis functionality with low production cost, ease of assembly, and adaptability.

Research Objectives

The main objectives of this project are as follows:

- To design and model a compact 5-axis CNC milling machine that meets defined mechanical and operational requirements.
- To integrate appropriate electrical and electronic components, including stepper motors, drivers, sensors, and motion controllers.
- To implement and configure a control system capable of synchronized multi-axis motion using available open-source or low-cost solutions.
- To fabricate, assemble, and test the prototype to validate its mechanical performance and machining accuracy.

Scope of the Project

The scope of this work covers the conceptual and detailed design, component selection, assembly, and testing of a functional 5-axis CNC prototype. It includes the integration of hardware and software subsystems necessary to achieve coordinated motion and machining capability. However, the project does not include advanced CAM algorithm development, industrial certification, or large-scale production optimization. The focus remains on delivering a working prototype that demonstrates both technical feasibility and educational value.

This thesis is organized as follows:

- **Chapter 1:** Overview of CNC machine fundamentals, including history, structure, classifications, and industrial applications.
- **Chapter 2:** Design methodology and architectural choices for the 5-axis CNC machine.
- **Chapter 3:** Fabrication, assembly, electrical integration, and control configuration of the prototype.
- **Annex:** Business Model Canvas (BMC) and financial analysis presenting the economic feasibility and potential for commercialization.

This project contributes to the ongoing effort of advanced manufacturing technologies, providing a foundation for educational institutions and small innovators to explore complex machining processes with affordable and scalable tools.

CHAPTER I

CNC Machine Fundamentals

Introduction

As manufacturing demands grew more complex, traditional manual machining could no longer guarantee the precision, consistency, or productivity required in modern industries. Advances in digital technology created a need for systems capable of reliably and repeatedly producing accurate components without relying on human dexterity. This need led to the development of Computer Numerical Control (CNC) machines, which automate cutting operations by converting computer-generated instructions into controlled mechanical motion. CNC technology, therefore, emerged as a response to the limitations of manual machining, enabling higher accuracy, improved repeatability, and efficient production of intricate geometries.

This chapter gives a concise overview of CNC fundamentals. It briefly notes the historical origins of numerical control and defines key terms (NC, CNC). It also describes the main machine subsystems and the fundamental motion-control concepts that underlie CNC operation, and presents common classification schemes and industrial applications. These basics establish the technical vocabulary and framework used throughout the thesis.

I.1 History

Numerical control began as a practical way to make machines follow stored instructions instead of relying on a human operator. Early NC systems used electrical and electromechanical parts to drive servomotors and follow simple motion programs. As electronic components and computers improved, the control logic moved from hardwired circuits to software and microprocessors. That change gave rise to computer numerical control (CNC), where software and stored program memory do most of the work that previously required physical wiring or manual adjustment.

Around 1947, John T. Parsons began experimenting with the idea of using numerical data to guide cutting tools, driven by the need to produce complex aircraft parts more quickly and accurately. Parsons developed methods to convert geometric information into motion commands that a machine could follow, and this early work

laid the conceptual foundation for later demonstrations and patents [74].

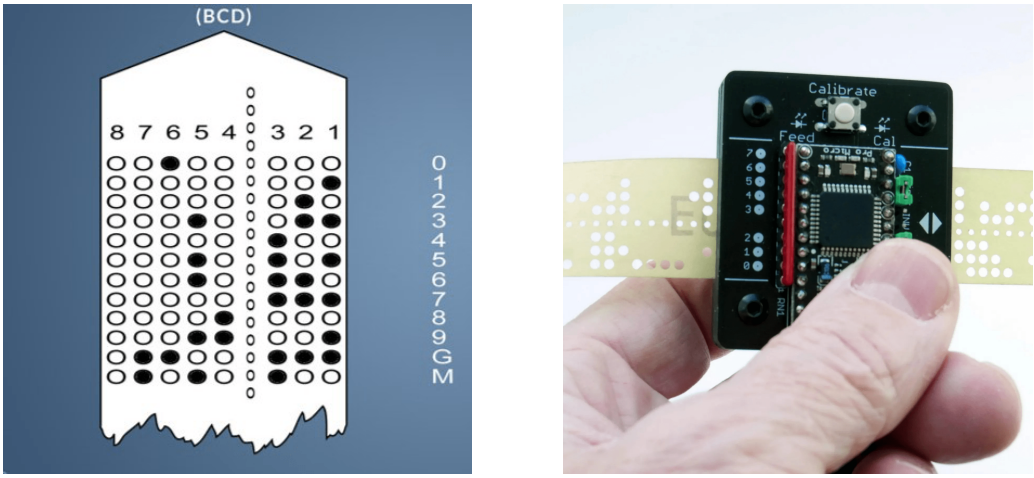
By 1949, the U.S. Air Materiel Command had recognized that aircraft and missile parts were becoming more complex and could not be produced reliably by manual methods alone. This urgent industrial need led to funding and contracts to explore automated solutions, and Parsons Corporation received support to develop practical NC techniques in coordination with academic partners [74].

Work continued under subcontract at institutions including the Massachusetts Institute of Technology. In 1951-1952, MIT and its servomechanism teams adapted existing milling equipment and demonstrated that a machine could follow punched-tape instructions to cut complex contours reliably. These demonstrations proved the basic idea: stored instructions could be translated into smooth tool-paths and repeatable parts [48].

After those early successes, the effort shifted to making programming and production practical for the industry. Higher-level programming tools (for example, APT), better controllers, and CAD/CAM integration simplified program generation. Over time, machine capabilities expanded: single-operation NC machines evolved into versatile CNC machining centers, and the number of controllable axes increased-leading to multi-axis machines (including 4-axis and 5-axis configurations) that allow more complex tool orientations and reduce the need for multiple part setups.

I.2 Definition of NC

Numerical control (NC) is a method for directing machine tools by means of encoded instructions rather than direct manual guidance. A program, originally stored on physical media, commands the machine where to move, how fast to feed, and when to change tools. The core purpose of NC is to replace manual positioning with a repeatable, data-driven process so that parts with complex shapes and tight tolerances can be produced reliably and consistently [53].



(a) punched tape (b) electronic tape reader

Figure I.1: Standard 8-channel punched tape

Early NC systems relied on punched cards and punched tape as the program carriers. The standard punched card commonly used in early installations had 80 columns and twelve possible punch positions per column, each column encoding a single character or numeric value; punched tape used a continuous strip with several parallel channels (typically 5–8 bits across) to encode longer sequences. These media allowed mechanical readers to feed a pre-recorded sequence of commands into the controller mechanically and in order, ensuring that tool motion followed the recorded program exactly, as illustrated in Figure I.1 [53, 120].

An NC setup is built from a small set of cooperating subsystems: the program source (cards or tape), a reader/interface unit, the control unit that interprets program data, drive electronics that power servomotors, and the machine mechanics (slides, spindles, and cutting tools). Early implementations used hardwired logic and electromechanical components to interpret holes and operate servos; as electronics and computing advanced, those interpretation and timing functions migrated into electronic controllers and software, forming the basis of modern CNC systems [53, 120].

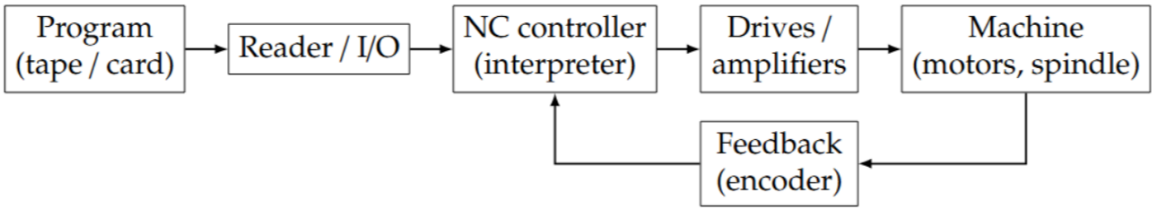


Figure I.2: Simplified block diagram of a numerical control (NC) system.

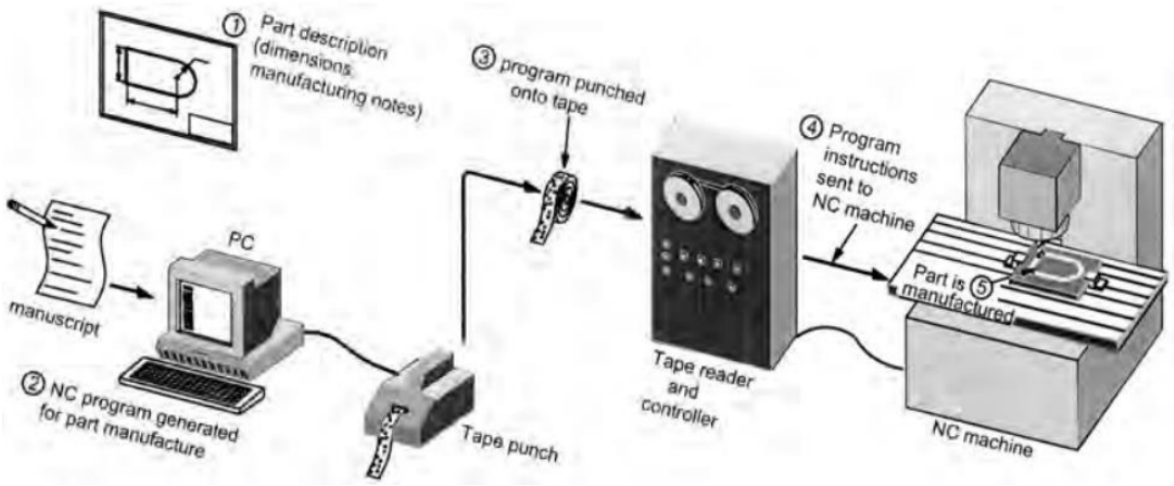


Figure I.3: NC machine components

The diagram in Figure I.2 & Figure I.3 shows the flow of information in a typical NC setup: stored program data is read and interpreted by the controller, which generates coordinated axis commands; drives convert those commands into motor torques and motion; finally, sensors provide feedback to correct errors. This representation helps to understand why NC originally relied on hardware logic (readers, relays, and hardwired sequences) and how modern systems moved those functions

into software and microprocessors to gain flexibility and memory-based program handling. [53]

I.3 Definition of CNC

Computer numerical control (CNC) is a system that turns a digital description of a part into precisely coordinated motion and auxiliary actions (spindle speed, tool change, coolant) that produce that part on a machine tool. In practical terms, a CNC system accepts a program (usually G-code), plans a sequence of coordinated axis motions from that program, and commands motor drives so the cutting tool follows the intended path with controlled speed and timing. The defining characteristic of CNC compared with early NC is that major control functions (program interpretation, interpolation, motion planning, and user interface) are implemented in software and executed by a stored-program controller rather than by fixed wiring or purely mechanical logic. [41]

At the workshop level, the CNC workflow has three visible layers. First, the design layer (CAD/CAM) produces geometry and converts it to toolpaths. Second, the program layer stores toolpaths in machine format (G-code) and transfers them to the controller. Third, the controller layer interprets G-code, executes motion planning, and issues real-time commands to motor drives. The controller's motion planner performs look-ahead and blending to prevent abrupt velocity or acceleration changes between adjacent motion segments; this is essential to maintain surface quality and avoid mechanical shocks. Drives convert those commands into currents/voltages for motors, and sensors (encoders, probes) provide feedback to measure and correct actual motion, as shown in Figure I.4. [3]

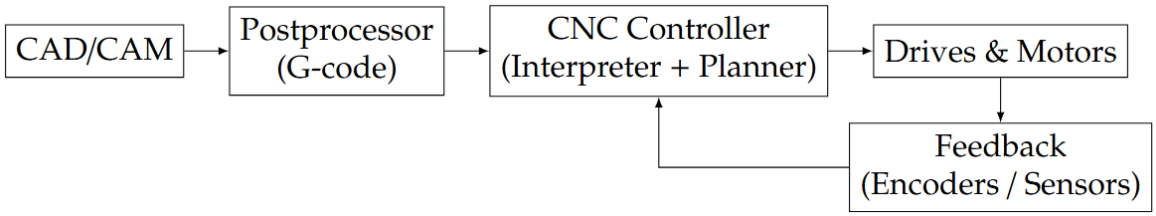


Figure I.4: Simplified process flow in a CNC system

Key motion concepts you will see repeatedly are interpolation, motion profiles, coordinate frames, and kinematic transforms. Interpolation breaks a geometric path (line, arc, spline) into small time-sliced commands each axis can follow; common modes are linear (G1) and circular (G2/G3) interpolation. Motion profiles (velocity, acceleration, jerk) and look-ahead let the planner blend corners and avoid abrupt changes that cause chatter or contour error. On multi-axis machines, the controller must also perform kinematic transformations (inverse kinematics) so that commanded tool positions map to motor positions for a given machine arrangement (e.g., head-table or table-table configurations on multi-axis machines). Tool radius/length compensation and work-coordinate transforms are additional features that make programs portable between work setups. [3]

Real machines have error sources that affect the final part: geometric errors (straightness, squareness), elastic deformation (structure bending under load), backlash and transmission compliance, thermal drift, controller quantization, and tool deflection. The practical metrics engineers use to qualify a CNC machine are resolution (the smallest incremental step), repeatability (how close repeated moves return to the same point), and accuracy (how close the actual position is to the commanded position). Compensation strategies include mechanical choices (stiffer frames, preloaded screws), control strategies (stiffness/position loop tuning, feedforward), and software compensation (backlash compensation, thermal compensation, and error maps). Understanding these sources and compensations is essential when selecting components or specifying performance for a prototype or production machine. [70, 55]

Short G-code example (how instructions look)

```
G21         ; set units to millimeters
G90         ; absolute coordinates
G1 X50 Y30 F200   ; linear move to X=50 Y=30 at feedrate 200 mm/min
G2 X80 Y30 I15 J0 ; clockwise arc to X=80 using center offset I=15, J=0
```

When the controller reads these blocks, it decodes units and mode, interpolates the linear and circular motions into coordinated axis trajectories, plans motion respecting feed and acceleration limits, sends axis commands to drives, and (in closed loop) uses encoder feedback to correct any deviation while cutting.

In the following table I.1, a structured comparison between NC and CNC systems is presented to highlight their fundamental technological differences.

Table I.1: Key differences between NC and CNC

	NC	**CNC**
Program Storage	Punched cards/tape	Electronic memory
Memory Capacity	Very limited storage	High-capacity storage
Control Logic	Hardwired circuit interpreters	Software-based interpreters
Logic Type	Fixed logic	Programmable logic
Interpreter Type	Relay-based	Microprocessor-based
Flexibility	Manual, difficult editing	Easy editing, updating, and transfer
Feedback	Often open-loop	Closed-loop control
User Interface	Mechanical switches and paper media	Graphical interface with HMI functions

I.4 CNC machine structure

The structure of a CNC machine is the physical and functional arrangement that supports motion, locates the tool and workpiece, and houses the subsystems required for machining. At a high level it groups the mechanical load-bearing elements (frame, bed, and spindle/head supports), the motion guidance and transmission (linear guides, ballscrews, belts or racks), the actuation and drive electronics (motors and drivers), the sensing and feedback elements (encoders, limit switches, probes), and the control/interface layer (CNC controller, HMI, and I/O). The way these elements are organized determines the machine's stiffness, natural frequencies, thermal behavior, and how cutting forces are transmitted, all key to achievable accuracy, surface quality, and dynamic performance. [103]

For a prototype, the structural goals are pragmatic: provide sufficient stiffness and geometric stability for the intended cutting forces, keep the design modular for easy adjustment and maintenance, and minimize sources of error (backlash, loose joints, thermal asymmetry). Emphasize straightforward, repeatable assembly, accessible service points (spindle mount, drive access, cable routing), and clear interfaces for future upgrades (different spindles, feedback options, or larger drives). Detailed frame layouts are treated in Chapter 2; here, the focus is on defining the subsystems and the practical design priorities.

I.5 CNC machines classifications

CNC machines are commonly classified according to different engineering viewpoints: what manufacturing function they perform, how many axes they control, how motion is realized and executed, and how the control system operates. Each classification highlights different trade-offs (cost, complexity, accuracy, and suitability for certain parts or processes) and helps guide architecture, control, and CAM choices for a given application.

I.5.1 By function

When we classify CNC machines by function we group them according to the primary mechanical task they are built to perform. This view is practical because the selected function strongly affects machine geometry, required rigidity, spindle choice, fixturing, and controller features. In other words, the machine that is best for one kind of work may be a poor choice for another simply because its components and design are optimized for different forces, motions, and production patterns. The paragraphs below describe four common functional classes: milling, turning, drilling, and non-traditional processes.

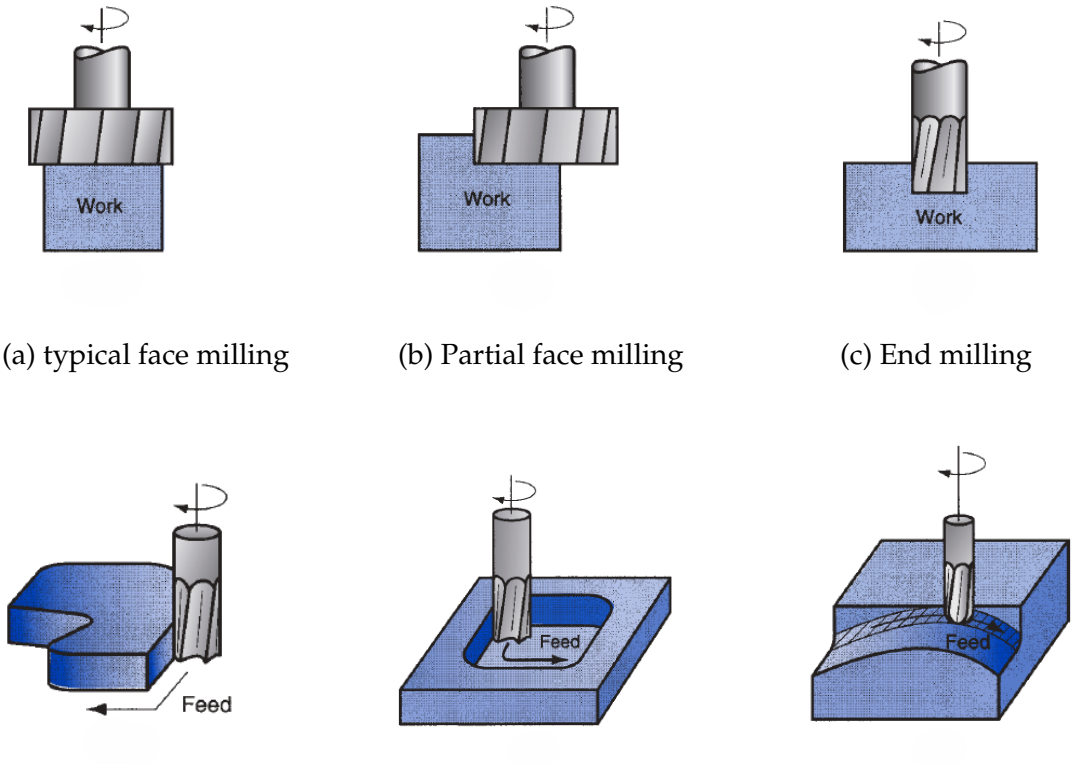
- **Milling machine**

  A milling machine removes material from a workpiece by means of a rotating cutting tool. The same basic machine can produce many different features by

changing the tool motion, the cutter type, or the cutting parameters. Below are the most common milling operations.

- **Conventional face milling:** Face milling uses a cutter whose cutting edges lie approximately on the periphery and on the face (end) of the tool; the cutter is fed across the top surface of the workpiece to produce a large, flat area. It is commonly used to 'clean up' a surface or to bring a part to a controlled thickness. The cutter removes a thin layer across a broad area in each pass.
- **Partial face milling:** Partial face milling is similar to face milling, but the cutter does not span the entire width of the workpiece. This happens when the cutter diameter is smaller than the feature width or when only a portion of the surface needs flattening. The result is the same type of flat surface, but only on a limited area.
- **End milling:** End milling uses a cylindrical cutter with cutting edges on the side and the tip. Because an end mill can plunge straight down and also cut sideways, it is suited for creating slots (narrow channels), grooves, and small feature details. End mills come in different tip styles (flat, ball-nose) so they can produce sharp corners or rounded profiles.
- **Profile milling:** Profile milling follows the outer boundary of a part to cut a contour or outline. If you need the external edge of a part to match a specified shape (straight or curved), profile milling traces that shape with the cutter, producing the finished outer contour.
- **Pocket milling:** Pocket milling removes material from inside a closed boundary to create a recessed area or cavity (a pocket). The cutter travels inside the boundary, progressively removing material until the desired depth and flatness are reached. Pocket milling requires careful planning of tool entry/exit and chip evacuation to avoid tool overload.
- **Surface contouring:** Surface contouring (or 3-D contouring) creates smoothly varying three-dimensional surfaces, for example, complex curved shapes on molds or aerodynamic parts. The cutter follows a series of closely spaced passes that together form the final curved surface; achieving a good surface finish requires appropriate cutter selection, step-over settings, and careful motion planning.

These milling operations illustrate how a single milling machine can perform a wide range of tasks simply by changing the cutter and the programmed toolpath. For a visual overview of the operations, see Figure I.5. [89, 88]



(a) typical face milling (b) Partial face milling (c) End milling

(d) Profile milling (e) Pocket milling (f) Surface contouring

Figure I.5: Illustration of common milling operations

Because the cutter pushes sideways against the material while it cuts, the machine must resist these **side loads** (forces perpendicular to the cutter axis). Resisting side loads requires a stiff column, rigid spindle mounting, and precise linear guides so the cutter tip stays on the intended path. Milling machines are therefore designed with stronger frames and higher-quality spindles than simple machines used only for drilling. Milling is very flexible; the same machine can make a pocket, a slot, or a curved surface, but that flexibility increases cost and maintenance requirements compared with single-purpose machines.

- **Turning machine**

  Turning machines (lathes or turning centres) work by **rotating the workpiece** while the cutting tool moves along one or more linear directions. Because the part spins, many turned parts are axisymmetric; their shape is the same around a central axis (for example, a shaft, a bolt, or a bearing journal). Axisymmetric means that if you rotate the part around its central axis, the profile does not change.

  Key elements in turning include the spindle: the rotating motor that drives the chuck, and a mechanical clamp with jaws that grip various sizes of parts, as shown in Figure I.6. Turning machines must provide a very well-balanced spindle and rigid support so the rotating part does not wobble; wobble reduces surface finish and dimensional accuracy. Turning centres are efficient for producing cylindrical features and are often simpler (and cheaper) than full

multi-axis milling centres when the production need is mainly turned parts. [89, 45]

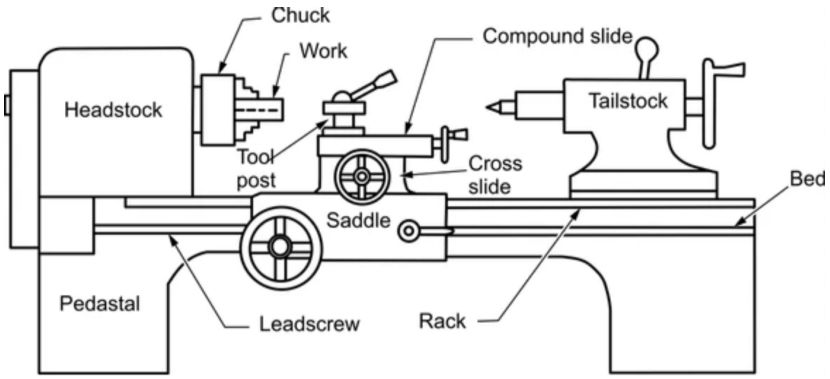


Figure I.6: Lathe machine illustration

- **Drilling machine**

  A drilling machine is specialized for producing holes. Drilling forces act mostly along the tool axis (axial forces), so the most important machine characteristics are axial stiffness and a spindle with low **runout** (runout is the deviation or "wobble" of a rotating part from its ideal axis, in this case, the spindle or tool; lower runout gives a cleaner, more accurate hole). Good drilling also requires efficient chip removal so the drill does not clog; this is why drilling cycles often include **peck drilling** (a machining technique for deep holes where the drill bit plunges partway, retracts to clear chips and allow coolant in, then plunges again in increments (pecks) until the full depth is reached) and canned cycles in the controller that automate repeated hole patterns.

  If the workshop simply needs many holes, a dedicated drilling machine or a drilling head is usually cheaper and easier to maintain than a full milling centre. However, a milling centre can also drill as part of its broader capability; the trade-off is higher purchase and running costs versus the flexibility to do more than just drill holes. [89, 54]

- **Others (EDM, laser, waterjet, etc.)**

  "Others" covers processes that do not remove material by a cutting edge rubbing the workpiece. Examples:

  - **EDM (Electrical Discharge Machining):** removes material by electrical sparks between an electrode and the workpiece. It is excellent for very hard materials and for producing fine cavities that are difficult to mill.
  - **Laser cutting:** uses a focused laser beam to cut, engrave, or mark various materials along a path. It is fast for thin sheets and non-contact (no tool wear), but creates a **kerf** (the width of material removed by the beam) and a heat-affected zone that must be considered.
  - **Waterjet:** uses a high-pressure fluid jet (sometimes with abrasive) to cut material; it produces no thermal damage but needs high-pressure pumps and proper fixturing.

Although these methods use different physical mechanisms, CNC control is still essential because the process must follow precise paths and timings. The planning and parameter choices (for example, spark gap in EDM or feed speed in laser cutting) follow the physics of the process rather than chip formation, but the external result, a toolpath that the machine follows, is still controlled numerically. [83, 45]

Choosing between a milling centre, a turning centre, a drilling machine, or another process depends on the task, required quality, and cost. If the primary need is a single repetitive function (for example, many identical holes), a dedicated machine (driller) often gives the best value: lower capital cost, simpler maintenance, and faster throughput for that task. If the parts require a range of operations (pockets, slots, faces, and holes), a milling machining centre delivers flexibility at a higher cost and complexity. Non-traditional processes are selected when material properties or feature types make mechanical cutting inefficient or impossible. In short, pick the machine that matches the dominant functions needed; the right match reduces cost and improves productivity. [83, 54]

I.5.2 By number of axes

CNC machines are often grouped by how many separate motions (axes) the controller can command. The axis count is a basic measure of capability: more axes usually mean more complex motion and greater ability to orient the tool relative to the part. Below are the common axis counts:

- **2-axis:** Two-axis machines typically provide motion on two linear directions (usually X and Y). They are suitable for simple planar cutting or routing tasks where depth (Z) is fixed or set manually. Programming and kinematics are simple, and these machines are commonly used for light routing, plotting, or operations where only planar positioning matters.
- **3-axis:** A three-axis CNC controls X, Y, and Z linear motions. This is the most common industrial configuration because it supports full 3-dimensional contouring with the tool axis fixed in orientation. A 3-axis mill can produce pockets, slots, faces, and many prismatic features by moving the cutter in three directions. For many parts, a well-built 3-axis machine offers the best balance of capability, cost, and programming simplicity.
- **4-axis:** A four-axis machine adds one rotational axis (commonly labelled A or B). The rotation may be used in two ways: indexed or continuous. In the indexed mode the rotary axis is repositioned to a specific angle and then held fixed while cutting proceeds on the linear axes. Indexing provides access to multiple faces without complex simultaneous motion and is easier to program and control than continuous rotary contouring. In continuous mode, the rotary axis turns while the linear axes move (for helical cuts or wrap operations). [17]
- **5-axis:** A five-axis CNC lets the tool tip and/or tool axis move with five degrees of freedom: three linear translations (X, Y, Z) and two independent rotations

(commonly A and B, or A and C depending on machine layout). There are two common practical modes of using five axes:

- **3+2:** also called positional 5-axis, two rotational axes are used to reorient (tilt) the tool, or the part, and then lock it; the three linear axes then perform the cutting. This mode is effectively a series of 3-axis cuts with different tool orientations and is much simpler to program and safer in terms of collisions.
- **Simultaneous 5-axis contouring:** the controller moves all five axes simultaneously so the cutter can trace complex surfaces while continuously changing orientation. In simultaneous 5-axis the controller computes coordinated trajectories for five actuators so the tool tip follows the programmed spatial path while the tool axis rotates to maintain the desired cutting direction. This involves two linked computations in real time, translation interpolation to position the tool tip along the path, and then kinematic transformation (inverse kinematics) that converts the desired tool pose (position + orientation) into the specific motor angles and linear positions for each axis. Simultaneous 5-axis, therefore, requires more advanced CAM toolpath generation, higher controller processing power, careful collision checking, and often more careful fixturing and low-profile tooling. [16]

The differences between *3+2* and *simultaneous 5-axis* are summarized in Table I.2 and illustrated in Figure I.7.

	3+2 (indexed)	**Simultaneous 5-axis**
Programming complexity	Low, fixed angles, simple CAM	High, dynamic angles, advanced CAM
Controller requirements	Basic controller, no blending	Fast controller with look-ahead and inverse kinematics
Collision risk	Low risk due to fixed and predictable angles	High risk because of continuously moving rotary axes
Surface quality	Good finish but requires re-clamping	Smooth finish with continuous motion
Typical use	Simple parts and multi-face machining	Free-form shapes and one-setup finishing

Table I.2: Indexed vs. simultaneous 5-axis milling

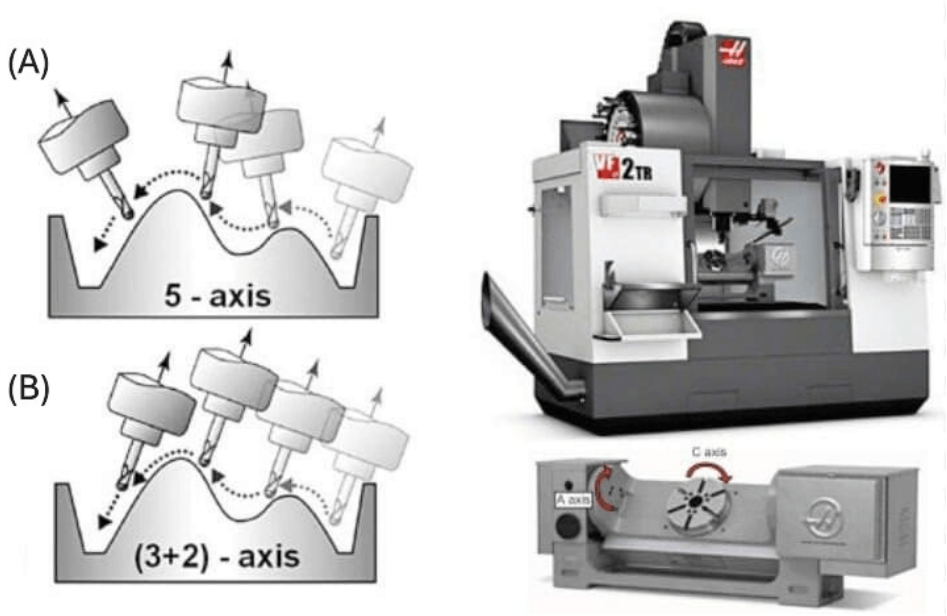


Figure I.7: Indexed vs simultaneous 5-axis milling

- **6+ axes:** Higher axis counts (6, 7 or more) commonly appear in robotic manipulators or specialized fixtures that combine multiple motions. These extra axes increase setup flexibility and automation but also raise the complexity of kinematic mapping, collision avoidance, and programming. For a prototype, extra axes are used sparingly and only when a clear functional benefit justifies the increased control and mechanical complexity.

A well-chosen axis count should match the part geometry and production goals: adding axes increases capability but also programming difficulty, controller cost and collision management needs. A careful balance (choosing 3, 3+2, or full 5-axis) usually gives the best return for a given design problem.

I.5.3 Based on motion systems

Motion-system classification groups CNC machines by how the controller generates and executes motion.

- **Point-to-point (PTP) control:** In point-to-point control, the machine is commanded to move the tool or workpiece between discrete positions; the exact path followed between points is not controlled. This mode is appropriate when only final positions matter (for example, drilling a set of holes). PTP systems are simple and cost-effective because they do not require high-rate interpolation or continuous coordination of multiple axes, as illustrated in Figure I.8. [107]

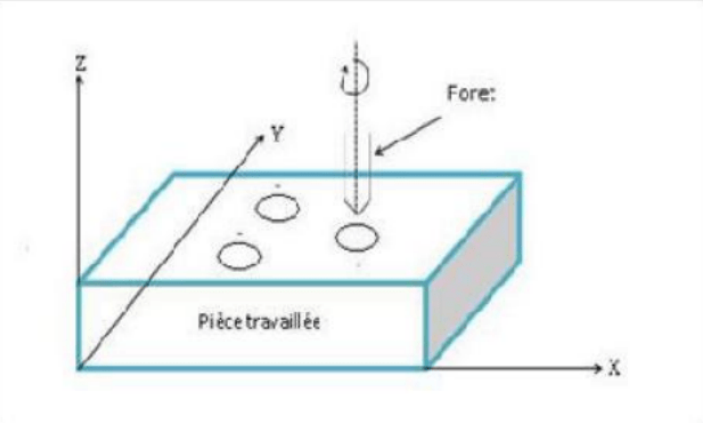


Figure I.8: PTP control

- **linear control:** Straight-line control guarantees that the tool moves along a specified straight path between points, typically in two axes simultaneously (for example X and Y), as shown in Figure I.9. This is useful for operations where the tool must follow a straight edge or cut. It sits between PTP and full contouring in complexity; the path is constrained but still simpler than arbitrary 3-D curves. [107]

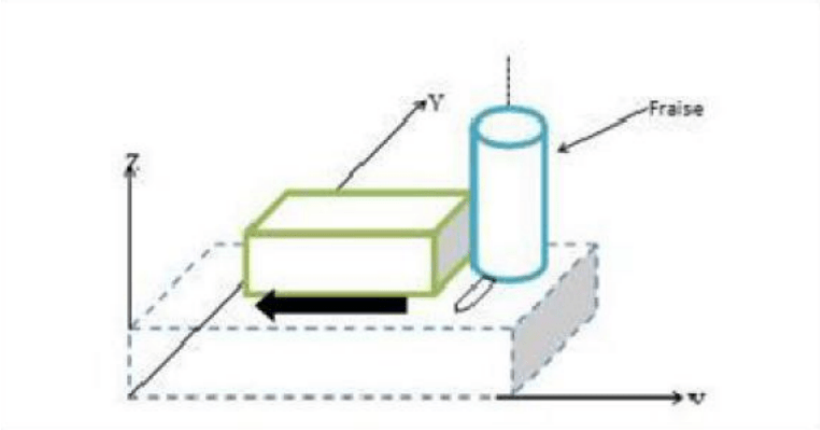


Figure I.9: linear control

- **Contouring / continuous-path control:** Contouring, also called continuous-path control, requires coordinated motion of two or more axes so the tool follows a prescribed geometric path (lines, arcs, splines) continuously, as illustrated in Figure I.10. Modern contouring controllers do three linked tasks in real time:
  - **Interpolation:** converts geometric segments (G-code blocks) into small time-sliced axis setpoints using linear, circular, or spline interpolation.
  - **Look-ahead and blending:** analyzes upcoming program blocks to adjust feedrate and acceleration smoothly at block junctions, preventing sudden jerks or feedrate drops.
  - **Trajectory planning:** computes velocity and acceleration profiles that respect axis limits and prevent overspeed or over-acceleration.

Blending and look-ahead are essential because many CAM-generated toolpaths are a sequence of short linear segments; without look-ahead, the controller would repeatedly stop or sharply change speed at each segment junction, harming surface finish and productivity. [107, 62]

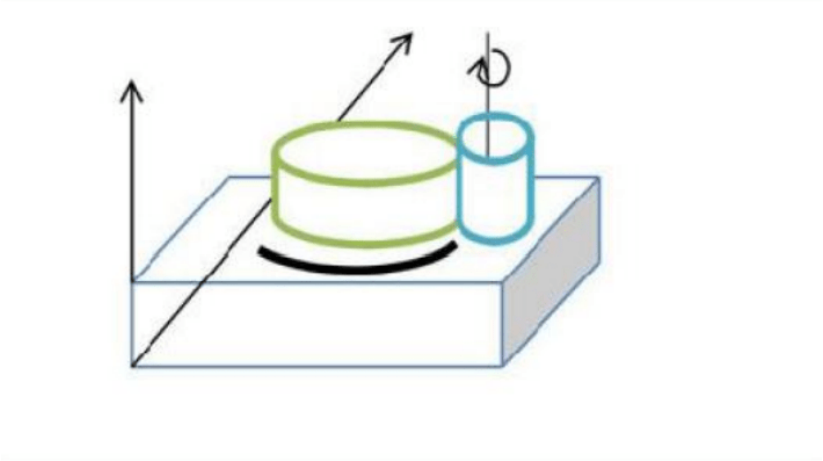


Figure I.10: Contouring control

Understanding these motion-system types helps pick the right controller features (interpolation types, buffer/lookup sizes, CPU capabilities) and the right CAM strategies.

I.5.4 By operating mode

Modern CNC machines are often classified by how they control and verify axis motion.

- **Open-loop systems:** Open-loop systems send step or pulse commands to the motor without direct position feedback. Stepper motors are the typical example, where each input pulse makes the motor advance one step and the controller assumes the motor followed the command. This simplicity keeps electronics and software straightforward and low-cost. The main risk is *lost steps*: if the motor stalls (for example under an unexpectedly high cutting force) the controller does not know the axis position has changed, so future moves are based on an incorrect assumed position. Open-loop systems are fine for light loads, low speeds, and simple prototypes where occasional re-homing is acceptable. [72, 98]

- **Closed-loop systems:** Closed-loop control means the drive or controller continuously measures the actual motion of an axis and compares it to the commanded motion; any difference (the *error*) is used to correct future commands so the axis follows the desired trajectory. The measurement typically comes from an **encoder** (a device that reports position) or a **resolver** (an electromechanical angle sensor). Encoders can be *incremental* (they report changes in position relative to a reference) or *absolute* (they report the absolute position

value). Higher encoder resolution (more counts per millimeter or per revolution) yields finer position feedback and allows tighter control. [98]

A standard closed-loop architecture for axis motion uses nested control loops. The outer loop is the **position loop** which runs at a lower rate and decides the desired position trajectory; it typically issues velocity or position setpoints to the inner loop. The inner loop is the **current or torque loop** (or velocity loop, depending on the drive) that runs at much higher frequency inside the motor drive and directly controls the motor torque/current to follow the setpoint. This separation lets the position loop focus on geometric tracking while the inner loop enforces force/velocity limits and handles very fast dynamics. Typical control laws are PID (proportional–integral–derivative) with added feedforward terms (velocity and acceleration feedforward) to reduce lag and improve tracking, as illustrated in Figure I.11.

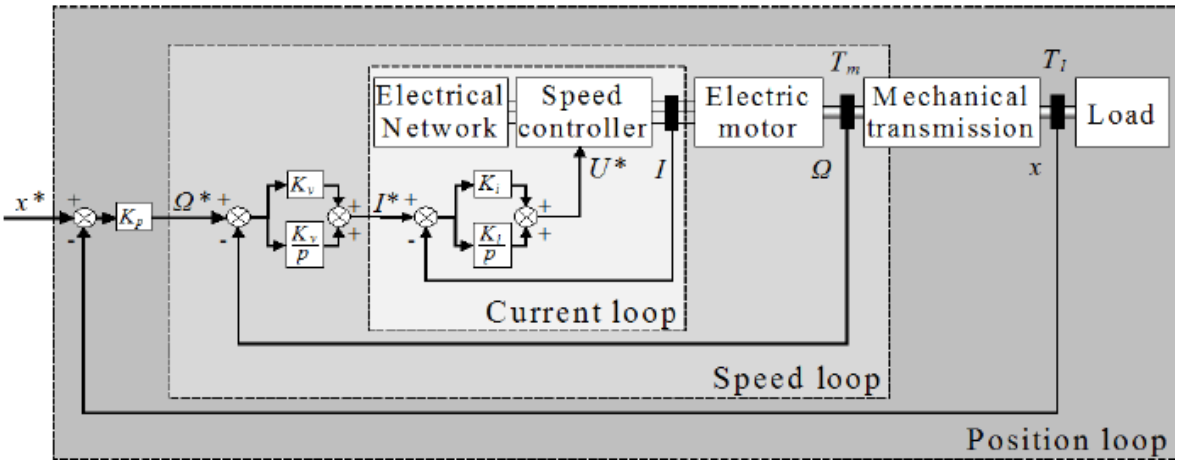


Figure I.11: nested loop

Closed-loop systems bring several practical advantages: they detect and correct lost steps or disturbances (for example, sudden cutting force spikes), they allow higher reliable feedrates under load, and they provide diagnostic signals (position error alarms) that help detect faults. Their main disadvantages are complexity and cost: they require encoders, more capable drives, and careful tuning. Important design parameters are control bandwidth (how fast the loop reacts), sensor resolution, and mechanical stiffness: a high bandwidth controller on a flexible structure can actually worsen vibrations if not tuned properly, because the controller may excite structural modes. Good practice is to align controller bandwidth with machine structural dynamics and to include feedforward and notch filters where appropriate. [49]

- **Hybrid systems:** A practical midpoint is to keep stepper motor drives, but add an encoder on the axis. The encoder verifies actual motion: when missed steps occur the controller can either correct automatically (if supported) or generate an alarm for a controlled stop. This approach preserves much of the simplicity and cost advantage of steppers while adding fault detection and improved robustness, a very reasonable choice for multi-axis prototypes, including 5-axis machines, where budget is limited but reliability matters. [98]

For prototype work, choosing the simplest mode that still meets accuracy and safety goals: open-loop for very low-cost, low-force axes; closed-loop for axes that carry heavy loads or that must guarantee position; and hybrid (stepper + encoder) for a balanced, budget-aware approach that improves reliability without the full cost of high-end servo systems, Figure I.12 shows the difference between open-loop and closed-loop stepper systems.

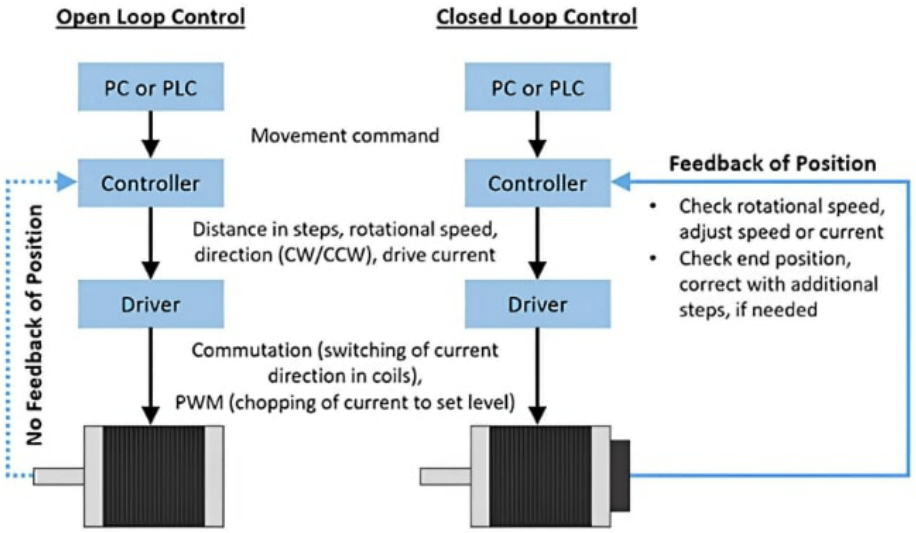


Figure I.12: Comparison between open-loop and closed-loop stepper motors

I.6 5-axis CNC machine classifications

Five-axis machines are commonly grouped by where their two rotary axes are located (on the head, on the table, or split between the two). The placement affects how the machine moves, how the controller computes motor commands (inverse kinematics), how easy it is to fixturing and avoid collisions, and the machine's stiffness and dynamic behaviour.

I.6.1 Head–head

- **Definition:** Both rotary axes are mounted in the spindle/head assembly, so the tool itself can tilt and swivel while the workpiece or table remains mostly static. In other words, the head carries the two rotations that change tool orientation relative to the part. [104]
- **Advantages:** Head–head layouts give excellent tool access: the cutter can approach the workpiece from many angles, which is especially useful for complex pockets or undercuts. They tend to have a small *footprint*, which is the physical floor area that the machine occupies, because the table does not need large rotary hardware. Also, since the head provides orientation close to the cutting

zone, some tool-length compensation and fine orientation control are easier to implement.

- **Drawbacks:** The head must carry the rotary motors and their gearing, which increases the moving mass on the head. Higher head mass raises inertia and can limit rotational acceleration and dynamic response unless the head is engineered very stiff and well-balanced. Increased mass and cabling at the head also complicate maintenance and service access. If the head is not sufficiently rigid, contour accuracy under side loads can suffer. [117]

I.6.2 Table–table

- **Definition:** Both rotary axes are mounted on the worktable. The part is oriented by rotating the table while the spindle provides the cutting motion. The rotary drives therefore act on the part rather than the head. [104]
- **Advantages:** Table-mounted rotaries often provide higher stiffness under cutting moments because the rotary bearings and drives are supported by a large table structure. This stiffness improves accuracy and resistance to bending when machining heavy parts or taking deep cuts. Table–table machines are therefore preferred for large components where support and rigidity matter.
- **Drawbacks:** Because the part rotates, fixturing must be *low-profile* (short in height) so the fixture and part do not collide with the spindle during rotation. Low-profile fixtures keep the part near the table surface and reduce the chance of collision. Rotating large or heavy parts increases the inertia the rotary drive must handle, requiring stronger (and more expensive) rotary motors and bearings. Also the machine footprint can be larger because the rotary table and its support structure occupy more space. [18]

I.6.3 Head–table

- **Definition:** One rotary axis is on the head and the other on the table. This splits orientation control between the tool end and the workpiece end. The controller must combine motions from both to realize the desired tool pose. This hybrid layout splits the two orientation degrees of freedom between the tool and the workpiece. The controller must coordinate both sources of orientation to achieve the commanded tool pose, which increases inverse-kinematics complexity but offers design flexibility. [104]
- **Advantages:** Head–table offers a balanced compromise; the table-mounted axis can give large-angle, stiff orientations while the head-mounted axis provides finer or quicker angular adjustments for accessibility. This reduces the head mass compared to head–head layouts while still maintaining good tool access in many cases. It can deliver a favourable mix of stiffness and accessibility for medium-sized parts.

- **Drawbacks:** Because orientation is produced by two separate actuators located in different parts of the machine, calibration and error compensation become more involved; small angular errors on either actuator compound at the tool tip. Collision checking is also more complex since both the tool and the workpiece can change orientation. Inverse-kinematics computations are more involved than for pure head or pure table-mounted systems and require careful controller calibration. [117]

Choosing between these families depends on your priorities. Head–head is for compact layout and maximum tool accessibility; Table–table is for the highest stiffness and heavy-part capability, and head–table when an economical compromise between access and rigidity is needed.

I.7 CNC machine applications

CNC machines are widely used across industry because they produce repeatable, high-precision parts with reliable dimensional control. Their programmability and automation make them suitable for both high-volume production.

- **Aerospace:** CNC machining is essential in aerospace for producing high-precision structural and engine components such as turbine blades, blisks (bladed disks), and complex cooling passages in hot-section parts. Aerospace parts demand tight tolerances, complex free-form surfaces, and high-quality surface finishes; CNC multi-axis machining (often 5-axis) enables these shapes in difficult alloys like titanium and Inconel while preserving material integrity and dimensional accuracy.
- **Automotive:** In the automotive industry CNC machines produce engine components (cylinder heads, blocks), transmission elements, prototypes, tooling and fixtures, and increasingly parts for electric vehicles. Modern automotive machining often uses multi-axis centres to reduce setups and improve surface quality, allowing faster product iterations and tighter tolerances that improve fuel efficiency and durability. CNC also supports rapid prototyping and low-volume production runs for new designs.
- **Electronics:** CNC is used in electronics for rapid prototyping of enclosures, milling of printed circuit boards (PCB prototyping), micro-machining of connectors, and fabrication of precise mechanical parts for electronic assemblies. Small CNC routers and specialized micro-mills let engineers produce and test PCB layouts, housings and mechanical interfaces quickly without large tooling lead times. This capability shortens product development cycles and enables low-volume, high-precision parts for sensors and consumer electronics.
- **Defense sector:** Defense and military applications rely on CNC for precision parts used in avionics, guidance systems, weapon platforms, and ruggedized mechanical subsystems. The defense sector values CNC for its ability to

machine difficult materials, produce complex geometries, and support quick-turn prototyping and low-volume manufacture for mission-critical components where reliability and traceability are required. Many defense suppliers use both traditional multi-axis CNC and advanced tooling strategies to meet certain specifications.

- **Health sector:** In medical manufacturing, CNC machining produces surgical instruments, diagnostic housings, and high-precision implants (orthopedic, dental) from biocompatible materials such as titanium and medical-grade stainless steels. CNC provides the dimensional accuracy, surface finish and repeatability necessary for implants and instruments, and manufacturers must combine good machining practice with regulatory quality systems (for example, FDA guidance and ISO standards) to ensure patient safety.

These five fields illustrate how CNC technology supports demanding requirements: complex geometry, tight tolerances, and repeatability. There are many other sectors that also use CNC (energy, tool & die, consumer products, research labs, and education). [97, 27]

I.8 Key advantages of CNC machines

CNC technology brings many practical benefits for both prototype development and production. The most important advantages are listed below:

- **High precision and accuracy:** CNC machines translate numerical programs into controlled motion with fine resolution, which enables tight dimensional tolerances and consistent part geometry across runs.
- **Excellent repeatability:** Once a program is proven, the same part can be produced repeatedly with minimal variation, reducing rework and scrap. This is especially valuable for medium and high volume production.
- **Increased productivity and throughput.** Automated tool changes, higher feedrates, and the ability to run unattended shifts enable much higher part output than manual machining. CNC also reduces non-productive time (fixturing, manual adjustments).
- **Flexibility and quick changeover:** Changing a part program or loading a different CAD/CAM file allows rapid switching between part types without major hardware reconfiguration, supporting short production runs and fast iterations.
- **Capability to produce complex geometries:** Multi-axis CNC systems (4/5-axis and beyond) can machine complex free-form surfaces and undercuts in a single setup that would be impossible or very costly with manual methods.

- **Reduced manual labour and operator skill dependency:** Automation reduces the need for repetitive manual operations and lowers dependence on artisan-level machine skill for routine production, while concentrating skilled work in programming and process planning.
- **Improved safety:** Operators are less exposed to cutting tools and chips because much of the work is automated and can be run from behind protective enclosures. CNC controls also include interlocks and limits that reduce the risk of accidents.
- **Better surface finish and part quality:** Accurate motion control, consistent cutting parameters, and advanced toolpath strategies produce superior surface quality and reduce the need for manual finishing.
- **Enhanced process traceability and documentation:** Digital programs, machine logs, and parameter records make it easier to document, reproduce, and certify production processes, which is an important advantage for regulated industries.
- **Lower material waste and more efficient cutting:** Optimized toolpaths and consistent feeds reduce overcutting and scrap, improving material utilization and lowering per-part cost.
- **Integration with CAD/CAM and digital workflows:** CNC fits naturally into modern digital design workflows (CAD → CAM → CNC), enabling simulation, collision checking and offline verification before the first cut. This shortens development cycles and reduces setup errors.
- **Scalability from prototype to production:** A validated CNC program can often be scaled from one-off prototypes to small-series production or adapted to higher-capacity machines with the same program logic, accelerating product ramp-up.

Taken together, these advantages explain why CNC is central to modern manufacturing,: it raises achievable quality, compresses development timelines, and enables production strategies that were impractical or impossible with manual machining. The particular benefits most relevant to a project (for example a 5-axis prototype) will depend on target tolerances, part complexity, and expected production volumes. [116]

I.9 5-axis CNC machine limitations

Although five-axis CNC milling offers superior flexibility, productivity and surface quality compared with three-axis machining, it is not without important technical and economic limitations that must be recognised when defining system requirements and selecting a suitable architecture. These limitations arise from the mechanical complexity of multi-axis structures, the increased burden on calibration and control, and the practical constraints of tooling, fixturing and process planning.

- **High Investment Costs:**
  The transition to 5-axis technology requires a substantial upfront and ongoing financial commitment. These machines are engineered with more complex drive systems, high-precision feedback devices, and advanced lubrication and safety networks. Consequently, the acquisition cost is significantly higher than that of an equivalent 3-axis machine. Beyond the initial purchase, businesses must account for recurring expenses related to specialized operator training, sophisticated software licensing, and the high cost of replacement parts for complex components.[11]

- **Complex Programming and Training Requirements:**
  Generating efficient, collision-free tool paths requires complex CAM programming and a high level of expertise. Operators must manage tool orientation selection and maintain constant engagement while navigating singularity avoidance(points where the machine's kinematic configuration loses a degree of freedom). Because of the increased number of moving elements (tilting heads, rotary tables, or both), the risk of catastrophic collisions multiplies. This makes virtual simulation or digital twin-based verification an essential, albeit time-consuming, part of the offline preparation process to prevent damaging incidents.[11]

- **Maintenance and Machine Availability:**
  The mechanical and control complexity of 5-axis systems creates a broader range of error sources, such as backlash, axis coupling, and encoder resolution limits. Rotary joints introduce geometric errors that are far more difficult to model than standard linear (X, Y, Z) axes[11]. To ensure machine availability, the system requires:

  - **Rigorous Servo Tuning**: Maintaining the kinematic relationship between all five axes.
  - **Thermal Management**: Addressing heat generated in rotary drives and bearings which can cause accuracy drift.
  - **Frequent Calibration**: Specialized volumetric compensation is often needed to correct for small angular misalignments that are amplified over long tool lengths.

- **Process Reliability and Quality:**
  Achieving consistent part quality is more difficult due to the extended kinematic chain. When a tool is tilted, the structural stiffness of the machine can decrease due to leverage effects, potentially leading to chatter or dimensional inaccuracies. Furthermore, tool-tip accuracy is highly sensitive to the combined errors of every axis. [11]

In practice, these limitations do not reduce the strategic importance of five-axis machining; rather, they highlight the necessity of appropriate design choices, accurate calibration, robust control strategies and well-trained operators to fully exploit its advantages. [11]

Conclusion

In this chapter, we established a comprehensive foundation on the evolution, structure, and operational principles of Computer Numerical Control (CNC) systems. Beginning with the historical progression from early numerical control to modern fully computerized architectures, we highlighted how technological advancements have shaped the machining landscape and enabled greater accuracy, flexibility, and productivity.

We then examined the key components that form the backbone of CNC machines, including the machine structure, mechanical drives, control units, and feedback systems. This exploration provided a clear understanding of how these subsystems interact to execute precise and repeatable machining operations. The chapter further outlined the main categories of CNC milling and turning operations, illustrating the machining processes that serve as the basis for complex manufacturing tasks. Additionally, we reviewed the major industrial sectors where CNC technology plays a decisive role, demonstrating its impact in fields such as aerospace, automotive, electronics, defense, and healthcare. Finally, we summarized the core advantages that make CNC machining indispensable in modern production environments.

Altogether, this introductory chapter serves as the conceptual and technical groundwork for the rest of this thesis. The next chapters will build upon this knowledge by focusing on the design, modeling, and realization of the proposed five-axis CNC milling machine, along with the control strategies and simulation approaches implemented throughout the project.

CHAPTER II

Design approach for a 5-axis CNC machine

Introduction

The objective of this chapter is to present a systematic engineering approach for the design, development, and validation of a compact 5-axis CNC milling machine prototype. The emphasis is on producing a design that balances mechanical stiffness, dynamic performance, control capability, and cost-effectiveness for educational and small-scale manufacturing applications. The chapter translates project goals into technical requirements and develops a clear sequence of design activities that guide component selection, system integration, and verification.

In the sections that follow, this chapter treats three closely related areas needed to build a functional 5-axis prototype: **mechanical structure** (frame layouts, guideways, transmissions, spindle/head arrangement and 5-axis kinematic options); **power and electronic systems** (motor selection, drives, power distribution, cabling, sensors and safety elements); and **control and software systems** (controller hardware and CAM/CNC integration). For each area the chapter discusses alternative solutions, compares trade-offs against the project goals, and provides practical guidance and reference designs to assist prototype development.

II.1 Requirements and specifications

This section collects the project's concrete requirements and technical specifications. The goal is to define, in practical terms, what the prototype must be able to do and which parameters will guide subsequent design choices. These specifications are engineering inputs (materials, tolerances, workspace, expected loads) that determine mechanical decisions, electronics sizing, and the control/software configuration.

- **Materials to be machined:** The choice of materials to be machined strongly influences spindle sizing, feed and speed selection, fixturing, and overall machine stiffness. Metals (aluminium, mild steel, alloyed steels) generally demand higher spindle power, stiffer frames, and more robust transmissions because cutting forces and heat generation are greater; they also more often require active

cooling or lubrication (flood coolant, mist or minimum quantity lubrication) to control tool temperature, clear chips, and preserve surface integrity. By contrast, wood and many plastics cut with much lower forces and thermal demand, which permits lighter structural choices, smaller spindles, and simpler tooling; in some cases, air blow or simple chip clearing is sufficient rather than full coolant systems. [59, 26]

- **Precision and tolerances:** Precision and tolerances are among the most critical specifications in the design of any CNC machine. They directly determine the machine's capability to produce parts that meet dimensional and geometrical requirements.

  Different machining applications require different levels of precision. For example, aerospace and medical components often require very tight tolerances, sometimes in the order of a few micrometers, whereas educational prototypes or general mechanical parts may allow larger tolerances without compromising functionality. Therefore, defining the required precision at the early design stage is essential in order to avoid unnecessary costs and overly complex design choices. The selection of the target precision is directly linked to the intended application of the machine; once the type of parts to be produced is identified, the corresponding tolerance and accuracy requirements can be established accordingly. [25]

  The required tolerance levels also influence the choice of motion and transmission components. The resolution and control mode of the motors, whether stepper or servo, affect positioning accuracy and repeatability, while the type of transmission elements such as lead screws or ball screws determines the level of backlash and mechanical precision. As a result, higher accuracy requirements generally lead to the selection of closed-loop actuation systems and low-backlash transmission mechanisms, which increase both system performance and cost [110].

- **Machine dimensions and capacity:** The overall dimensions of a CNC machine and its working capacity are directly determined by the size and type of parts that the machine is intended to produce. The workspace, often defined by the travel limits along the X, Y, and Z axes, must be large enough to accommodate the maximum dimensions of the workpieces while also allowing sufficient clearance for tool movement and fixturing.

  Modifying the machine's working envelope introduces significant technical implications. Changes in machine size affect structural rigidity, dynamic behavior, and positioning accuracy, while also influencing the selection and dimensions of mechanical components such as transmission systems. Larger machines generally require more material, longer motion components, and more powerful drive systems, which increases overall manufacturing complexity, weight, and cost.

  Therefore, the definition of machine capacity must be carefully balanced

with the intended application. Oversizing the machine leads to higher cost and reduced precision, while undersizing it limits the range of parts that can be produced. Establishing appropriate workspace dimensions at the early design stage ensures that the machine remains both technically capable and economically feasible [119].

- **Mechanical design choices:** The structural configuration of the CNC machine must be considered at the specification stage. The general frame topology, such as gantry-type or moving-table architectures, influences load distribution, stiffness, and accessibility to the workpiece. Although the detailed mechanical design is addressed later in the project, identifying these structural constraints early helps ensure that the selected configuration can support the required working volume and accuracy without excessive deformation or vibration during machining operations [111].

- **Electronics and power:** The electrical and electronic architecture of the CNC machine must be defined in accordance with the selected motors and drivers that are determined by the overall mechanical load, which then determines the required drive electronics and power supply capacity, while the number of axes defines the number of motors to be used and the necessary input/output interfaces. Proper dimensioning of the power distribution system, including protection devices and wiring, is essential to ensure reliable operation and user safety. In addition, thermal management and enclosure design must be considered, as all electronic components are typically integrated into a dedicated electrical cabinet that must provide adequate cooling, accessibility, and protection against electrical noise and environmental factors.[73, 1]

- **Control and software:** The control approach of the machine is based on the selection and configuration of an existing controller platform, either open-source or commercial, rather than the development of a custom motion control kernel. The chosen software must support essential CNC functions such as axis mapping, homing procedures, probe cycles, G-code interpretation, and the management of input/output signals. It must also be capable of handling the selected machine kinematics and enforcing motion limits, safety interlocks, and fault handling.

- **Cost and component availability:** Setting a realistic project budget and preferring off-the-shelf components when they meet the requirements, as this reduces development time and simplifies integration. Component selection should also take into account delivery lead times, vendor support, and the possibility of replacing or upgrading parts in the future in order to maintain system modularity.

  Budget priorities commonly follow a structured order: the mechanical structure and spindle are addressed first due to their influence on stiffness and cutting capability, followed by motion components such as drives and encoders, and finally auxiliary systems including coolant delivery and tool changing. Long-

lead components should be identified and recorded early so that the purchasing process does not delay the fabrication and assembly stages.

Together, these specifications and requirement themes interact closely, forming the engineering inputs used to design a 5-axis CNC machine.

II.2 CNC machine architecture

This section translates the project requirements into a compact system view that shows how mechanical hardware, power/electronics and control software interconnect to produce coordinated multi-axis motion. The architecture emphasises clear separation of responsibilities: the mechanical subsystem provides the moving elements and tooling interface, the electrical subsystem supplies power and closed-loop signals, and the control/software subsystem issues motion commands, enforces safety and hosts the human–machine interface.

Figure II.1 presents a compact interaction map between the three main domains: mechanical, electrical and software. It is intended as an early-design checklist: each arrow describes a class of constraints that designers must check when moving from requirements to specific choices (for example, how mechanical stiffness sets sensor and drive needs, or how control bandwidth limits actuator selection).

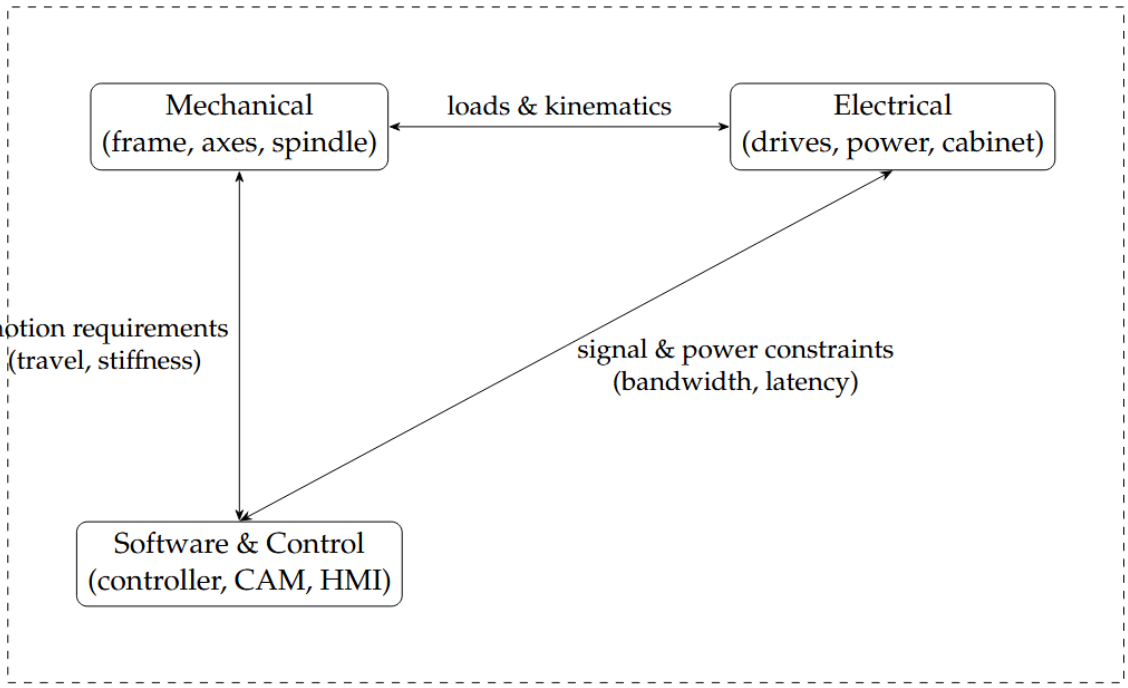


Figure II.1: High-level interaction map

Figure II.2 is an illustrative wiring diagram showing how a controller is typically connected to drives, motors, sensors/encoders and the power supply. The illustration highlights the main connection zones and practical details such as power entry; it

serves as a mid-level reference that links the high-level domain map to the lower-level wiring and cabinet decisions.

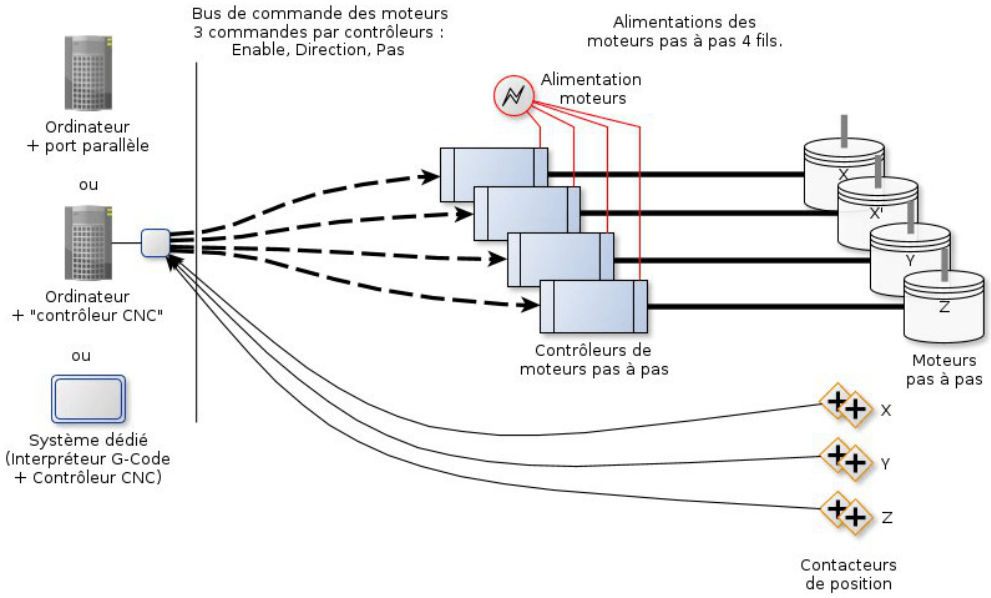


Figure II.2: Illustrative wiring and connection diagram of a 3-axis CNC

Figure II.3 provides a decomposed operational view of information and power flow during machine use. It expands the illustration into explicit signal and power paths: motion commands flow from the controller to the drives (step/dir), drives supply current to motors to move the mechanical axes, and encoders/sensors feed back position and status data to the controller. The HMI workstation uploads programs and retrieves logs, while the power cabinet distributes DC power to drives and controller.

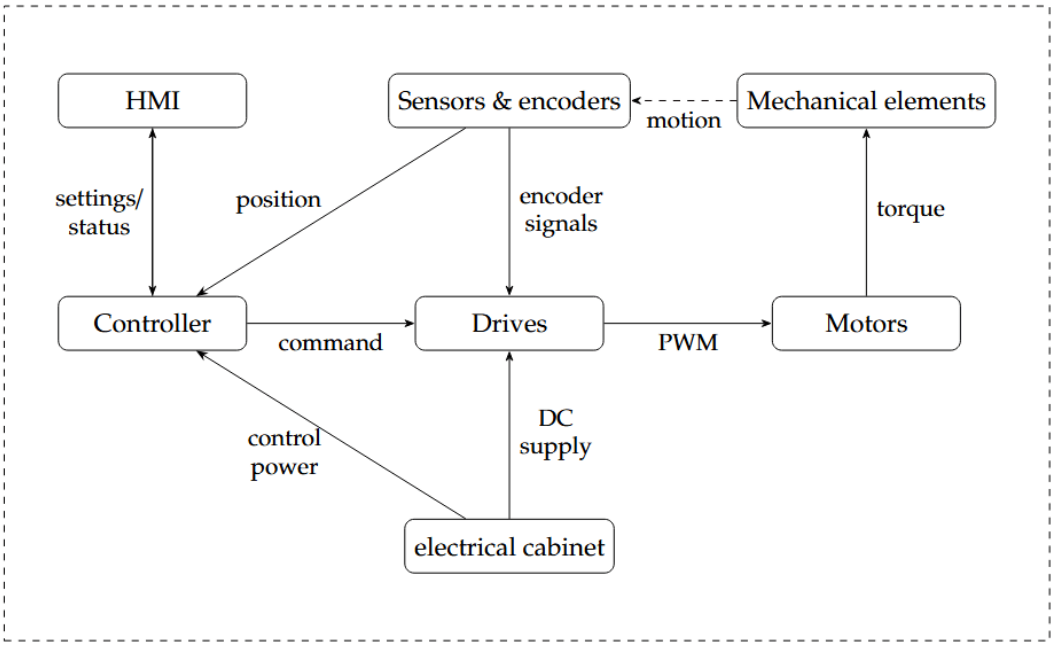


Figure II.3: Operation and power flow

II.3 Proposed design alternatives

Design alternatives are the candidate solutions considered for each major subsystem (mechanical, electrical/electronic, and control/software). Each alternative represents a different balance; comparing them objectively requires simple, repeatable checks, and a clear statement of how the choice supports the stated requirements. Selecting among alternatives concentrates on the combinations that satisfy material, tolerance, and budget constraints while minimising implementation risk.

II.3.1 Mechanical architecture and component selection.

Mechanical alternatives cover the key hardware choices that most influence accuracy and robustness, like the global frame layout, the structural construction method, linear guidance options, etc. Each option should be evaluated against the same criteria (stiffness, expected cutting load, ...) so that later selection can be justified and verified experimentally.

II.3.1.1 Frame layout

Frame layout is described along two independent lines: the *Frame Design* (how the linear and rotary axes are placed and move relative to the workpiece) and the *structural construction* (how the frame is built and from what materials). Separating these ideas keeps geometry/kinematics distinct from material and manufacturing choices, and simplifies later trade-offs between accessibility, stiffness and manufacturability.

II.3.1.1.1 Frame Design

Several linear-axis arrangements are widely used in 5-axis CNC milling machines, selected based on the required workspace, stiffness, and machine footprint. Each configuration specifically defines how the X, Y, and Z axes are implemented and how the spindle or head is supported. The most common arrangements are summarized below:

moving gantry (moving column)

- **Description:** A rigid bridge (gantry) spans the work area. The bridge translates along the X direction. The Y motion is implemented by a carriage on the bridge. The Z-axis consists of a vertical slide mounted on the carriage, with the spindle fixed at the end of it. Long X travel is often driven by two synchronized motors (one at each end of the bridge) to reduce twist and maintain squareness. (See Figure II.4.) [56, 19]
- **Advantages:** High stiffness across long travel distances; uniform dynamic performance over the entire table; ideal for large workpieces.
- **Drawbacks:** The overall machine footprint is larger and heavier; there is a potential for structural deflection (head sag) if the bridge is insufficiently rigid.

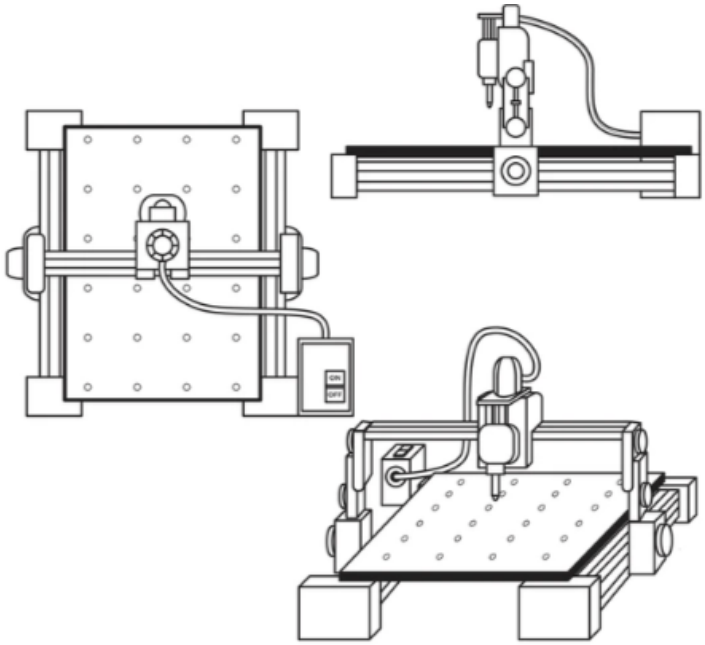


Figure II.4: Gantry type CNC

Moving bed (fixed bridge)

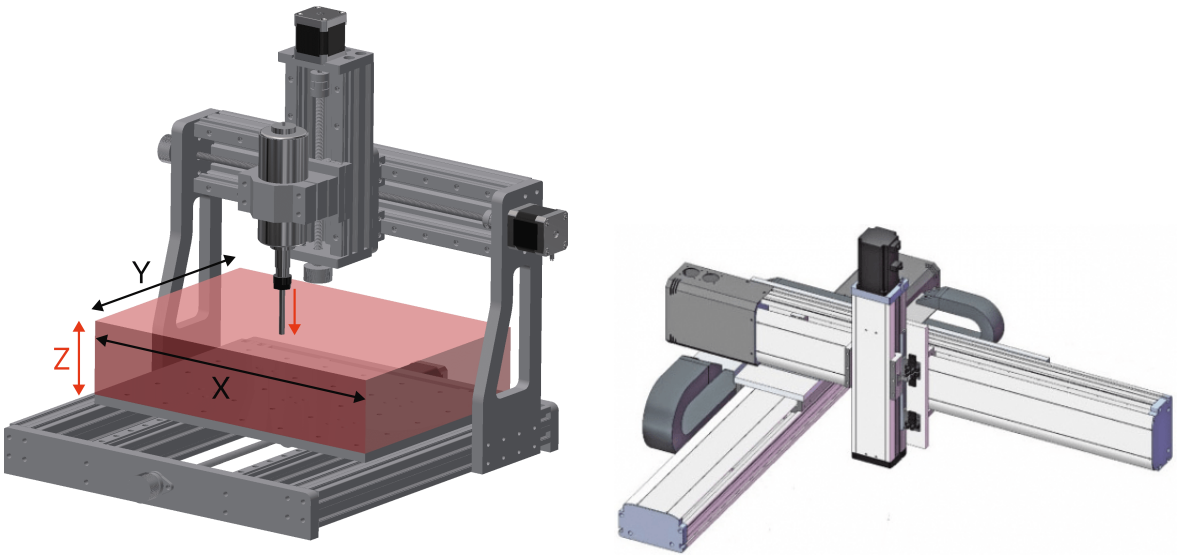
- **Description:** In a fixed-bridge design, the portal remains stationary, supporting the Y and Z-axis slides. The X-axis motion is handled by the table, which carries the workpiece. This layout ensures the spindle is housed within a stiffer frame for enhanced stability. Additionally, placing the long-travel drive motors on the bed (rather than the bridge) reduces the moving mass of the head, allowing for smoother acceleration and higher precision. (See Figure II.5a.) [56, 19]
- **Advantages:** Excellent structural support and rigidity; suitable for high-precision machining; reduced deflection under heavy cutting loads.
- **Drawbacks:** Larger floor space requirement relative to work volume; high moving mass can limit acceleration.

Cantilever

- **Description:** The structural architecture of a cantilever CNC machine is characterized by its reliance on a single, robust vertical column that serves as the foundational support for the entire moving assembly. Extending horizontally from this central column is a cantilever arm, which facilitates lateral translation along the Y-axis and houses the spindle or cutting head. Longitudinal motion along the X-axis is achieved through one of two primary configurations, either the entire column assembly traverses a dedicated linear rail, or the column remains stationary while a moving worktable translates the workpiece. Completing the machine's three-dimensional range of motion, the Z-axis provides vertical travel and is typically positioned at the distal (free) end of the cantilever arm.(See Figure II.5b.) [43]

- **Advantages:** Compact footprint; allows easy loading/unloading; ideal for small parts, educational equipment, or light-duty prototyping.
- **Drawbacks:** Reduced stiffness; limited suitability for heavy cutting or long travel ranges; increased sensitivity to vibration.

These three arrangements represent the majority of practical linear-axis designs for milling prototypes. Each provides a distinct balance between accessibility, stiffness, table size, and mechanical complexity.



(a) Moving bed type CNC (b) Cantilever type CNC

Figure II.5: CNC types

II.3.1.1.2 Structural Construction

The structural frame of a CNC machine is a key part of its rigidity, damping, and overall accuracy. Several construction approaches are commonly used, ranging from simple DIY solutions to more advanced industrial structures.

- **Aluminum extrusion**
  - **Description:** Aluminum extrusion frames use modular profiles that can be assembled with standard fasteners and adjusted relatively easily during the design stage, as shown in Figure II.6 (a). This makes them especially practical for prototype machines, where changes in geometry, component layout, or axis positioning may still be needed during development. Compared with heavier frame solutions, they are simpler to build and modify, but their lighter structure usually limits rigidity under more demanding cutting conditions. [7]
  - **Advantages:** Easy to machine, modify, and assemble; flexible for prototyping.
  - **Drawbacks:** Lower rigidity; less suitable for heavy cutting forces.

  - **Suitability:** Best for small-scale prototype machines and educational projects.

- **Welded steel frame**
  - **Description:** Welded steel frames are built by joining steel sections or plates into a single rigid structure, which gives them a stronger mechanical behavior than lightweight modular frames. The typical structure of a welded steel CNC frame is illustrated in Figure II.6 (b). They are often chosen when the machine must support larger loads or better resist deflection during machining. However, because welding can introduce distortion, the frame usually requires careful alignment and, in some cases, post-weld machining of reference surfaces to recover accuracy. [4, 7]
  - **Advantages:** High stiffness and load capacity; stronger than aluminum extrusion.
  - **Drawbacks:** Requires alignment and possible post-weld machining; heavier.
  - **Suitability:** Suitable for medium-sized machines with higher cutting force requirements.

- **Epoxy granite / Mineral composite frame**
  - **Description:** Epoxy granite, also called mineral casting or mineral composite, is produced by mixing mineral aggregates with epoxy resin and casting the mixture into a mold that defines the machine structure. In practice, this means the builder must prepare the mold, control the mix composition carefully, pour the material properly, and then leave it to cure for a sufficient time before finishing or mounting the remaining components. This fabrication route is more time-consuming than metal framing, but it gives a dense structure with strong vibration damping, which is one of the main reasons it is used for precision machine-tool bases and columns. As shown in Figure II.6 (c). [4, 7]
  - **Advantages:** Good vibration damping; stable and strong.
  - **Drawbacks:** More complex fabrication; requires mold and curing.
  - **Suitability:** Ideal for builders seeking heavy, low-vibration structures.

- **Cast iron frame**
  - **Description:** Cast iron frames are the traditional choice in many industrial machine tools because they combine high mass, good damping behavior, and long-term dimensional stability. Their large mass helps reduce the influence of vibrations, and their structure is well-suited for precision applications where stable machine behavior is more important than easy fabrication. Compared with prototype-oriented frame solutions, cast iron is much less convenient to produce, since it generally requires casting facilities and heavy machining, but it remains a reference material for production-grade machines. A cast iron machine base is shown in Figure II.6 (d).[4, 7]

- **Advantages:** High rigidity; excellent damping; stable over time.
- **Drawbacks:** Difficult to fabricate; heavy; requires casting and machining.
- **Suitability:** Best for industrial machines where performance is prioritized.

In some builds, hybrid frames can also be used, combining two different structural ideas to better match the project requirements. For example, an aluminum extrusion structure can be reinforced or filled with epoxy granite to improve stiffness and damping while keeping some of the modularity of the original frame. The final choice always depends on the build requirements and specifications.[7]



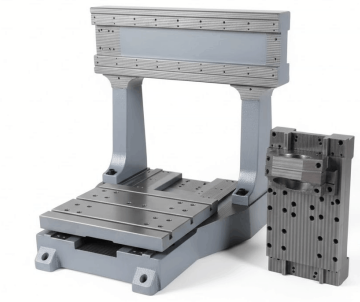
(a) Aluminum Extrusion CNC frame



(b) Welded steel CNC frame



(c) Epoxy granite CNC frame



(d) Cast iron CNC frame

Figure II.6: CNC structural Construction frames

II.3.1.2 Linear motion guidance systems

The linear motion guidance system ensures smooth and controlled translation of the machine axes, and it has a direct influence on rigidity, accuracy, and motion quality. Several guidance solutions are used in CNC machines, ranging from simple

low-cost arrangements to highly specialized precision systems. The following options summarize the most common approaches used in prototype and production machines.

- **V-wheels on V-slot profiles**
  - **Description:** This is one of the simplest guidance solutions used in lightweight CNC machines. As shown in Figure II.1 (a), the carriage rolls directly on a V-shaped aluminum profile using matching wheels, so the motion path is easy to visualize: the wheels stay engaged in the beveled edges of the profile and guide the axis along a straight line. The system is practical for fast assembly and easy adjustment during the prototype stage, especially when the frame itself is also built from extrusion profiles. It is a simple way to combine structural support and motion guidance in one modular solution.[13]
  - **Advantages:** Low cost, easy assembly, and simple maintenance.
  - **Drawbacks:** Lower stiffness, lower accuracy, and more sensitivity to wear.
  - **Suitability:** Suitable for small hobbyist machines and light prototype builds.
- **Round shaft guides**
  - **Description:** Round shaft guidance uses cylindrical shafts and bearing blocks or linear bushings that move along them. In practice, the shaft acts as the straight reference path, as shown in Figure II.1 (b), while the bearing block surrounds it and allows smooth motion with relatively low friction. Compared with V-wheel systems, it usually gives a more controlled motion path. It is often used when the machine needs a moderate level of precision without moving to a fully industrial guideway system.[82]
  - **Advantages:** Simple, affordable, and smoother than wheel-based guidance.
  - **Drawbacks:** Limited rigidity and lower load capacity than profile rail systems.
  - **Suitability:** Suitable for light CNC machines and moderate-precision motion stages.
- **Profile rail ball guides**
  - **Description:** Profile rail guides use a machined rail and a carriage with recirculating rolling elements to produce accurate linear motion. As shown in Figure II.1 (d), the carriage moves along the rail through guided rolling contact, so the system behaves much more rigidly than simpler shaft or wheel-based options. This increased rigidity stems from the larger contact area, which enables the carriage to resist tilting under cutting loads. That is why profile rail guides are often the first system people associate with proper machine-tool construction. They represent a balance between precision, stiffness, and practical installation.[82, 95]

  - **Advantages:** High accuracy, good rigidity, and wide industrial availability.
  - **Drawbacks:** More expensive and more sensitive to installation quality than simpler guides.
  - **Suitability:** Suitable for most serious CNC prototype machines and many industrial applications.

- **Cross-roller guides**
  - **Description:** Cross-roller guides use precision rollers arranged in an alternating crossed pattern inside the carriage, as shown in Figure II.1 (c). This geometry allows the guide to support loads effectively while keeping the motion smooth and compact. Compared with standard rail systems, the key difference is that the rollers are arranged to control movement more tightly, which gives the carriage a very stiff feel and makes it especially suitable for short-stroke precision motion. This type is typically used when high rigidity and accurate positioning are required over a limited travel range.[95]
  - **Advantages:** Very high rigidity, compact design, and high guidance accuracy.
  - **Drawbacks:** Limited stroke and higher cost than common rail systems.
  - **Suitability:** Suitable for precision machines and specialized motion systems.

- **Air bearing systems**
  - **Description:** Air bearing systems support the moving part on a thin film of pressurized air instead of direct mechanical contact. Because there is no rolling or sliding contact, the motion is extremely smooth and avoids the friction and backlash effects found in mechanical guides. This makes the system very different from the common CNC guidance solutions used in milling machines, but it also means that it requires a clean air supply and a more advanced setup. These systems are generally used when vibration-free motion and extremely high repeatability are required.[95]
  - **Advantages:** Extremely smooth motion, very high precision, and no mechanical contact.
  - **Drawbacks:** Complex, expensive, and requires a clean air supply.
  - **Suitability:** Suitable for ultra-precision and specialized high-end applications.

In practice, the selection of a linear motion guidance system represents a compromise between cost, required accuracy, structural rigidity, and ease of integration with the machine frame. Simpler guidance solutions are often sufficient for lightweight or educational machines, while high-precision systems become necessary when cutting forces, positioning accuracy, and long-term reliability are critical design constraints. The difference is presented in Table II.1 for better clarity. Therefore, the choice of

guidance technology must be made in parallel with the overall mechanical design of the CNC machine, rather than as an isolated component decision.



(a) V slot wheels



(b) Round shaft guides



(c) Cross-roller guides



(d) Profile rail ball guides

Figure II.7: Linear Motion Guidance Systems

Guidance type	**Cost**	**Rigidity**	**Typical applications**
V-wheels	Low	Low	Hobbyist machines and lightweight prototype CNC systems
Round shaft guides	Low–Medium	Medium–Low	Light-duty machines and educational motion systems
Profile rail ball guides	Medium	High	General-purpose CNC machines and most industrial equipment
Cross-roller guides	High	Very high	Precision stages and short-stroke high-accuracy mechanisms
Air bearing systems	Very high	Extremely high	Ultra-precision and vibration-sensitive applications

Table II.1: Comparison of common linear motion guidance systems

II.3.1.3 Linear transmission systems

The linear transmission mechanism is responsible for converting the rotary motion of the motor into linear movement along the machine axis. In a CNC machine, this choice has a direct impact on travel speed, positioning accuracy, load capacity, stiffness, and overall efficiency. The final selection depends on the intended application, since each mechanism offers a different balance between simplicity, precision, speed, and cost.

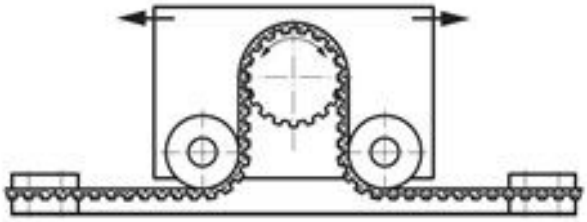
- **Timing belt actuators**
  - **Description:** A timing belt drive is a linear transmission system that utilizes a toothed belt and pulleys to convert rotary motor motion into precise linear translation. Depending on the specific requirements of the machine, these systems are typically configured in one of two primary layouts.

    In a closed-loop layout, the belt forms a continuous circuit around a drive pulley and an idler pulley. Both ends of the belt are secured to the carriage, causing the carriage to move in unison with the belt segment, as shown in Figure II.8 (b). This design is widely used due to its simplicity and the ability to keep the drive motor stationary on the machine frame.

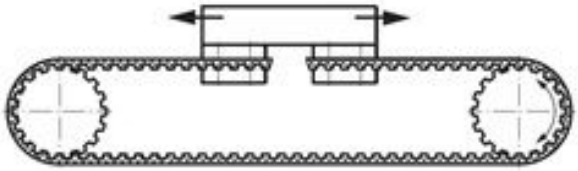
    In contrast, a fixed-end layout involves anchoring both ends of the belt directly to the machine structure, with the carriage housing the motor and the drive pulley, as shown in Figure II.8 (a). This configuration allows for two primary applications: the carriage can move along the belt, adding the motor's weight to the moving load, or the carriage can remain stationary while the entire actuator body acts as the moving component.

    In the latter case, which is a common application for this layout, the additional load becomes the weight of the entire actuator assembly. Although both configurations increase the total moving mass, this layout is often selected because it presents significantly fewer tensioning challenges than closed-loop systems.

    Regardless of the configuration, the fundamental principle remains the same, the interlocking of the pulley teeth with the belt profile ensures a positive, non-slip transfer of power to produce controlled linear motion along the axis.[112]



(a) Fixed-end layout



(b) Closed-loop layout

Figure II.8: Timing belt drive layouts

The linear travel produced by one pulley revolution depends on both the belt pitch p and the number of pulley teeth z_p. Each time the pulley completes one revolution, every tooth of the pulley engages one belt tooth, and the belt advances by one pitch length per tooth. The resulting linear displacement (Resolution) can therefore be written as:

$$x_{\text{rev}} = z_p\, p \implies x_{\text{mm}} = \frac{z_p\, p}{s\, m_s}$$

where s is the motor steps in one revolution, and m_s is the microsteps of a stepper motor (the number of steps a full step is subdivided into), the equation shows that the pulley tooth count and the belt pitch together define how far the carriage moves for each motor revolution. A belt with a larger pitch increases the distance traveled per revolution, while a smaller pitch provides finer positioning resolution.[76]

Because the pulley pitch diameter d_p is directly linked to the belt pitch p and tooth count z_p, as demonstrated in Figure II.9, its value is not independent, but can be expressed as

$$d_p = \frac{z_p\, p}{\pi} \implies x_{\text{rev}} = d_p\, \pi$$

This means that changing pulley diameter necessarily implies a change in tooth count or belt pitch. In practice, the belt pitch is usually fixed by the chosen belt family, and the axis characteristics are adjusted by selecting an appropriate pulley tooth count.[94]

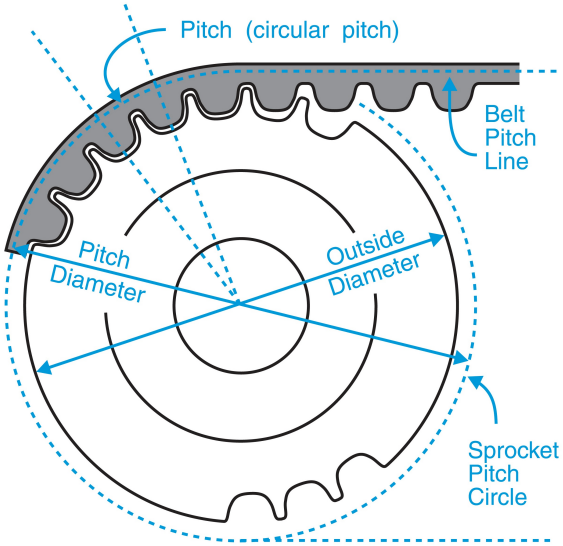


Figure II.9: Timing belt Pulley Pitch Diameter and belt pitch

The linear speed of the axis is also directly related to the pulley rotation speed. If the pulley rotates faster, the belt advances faster, and the carriage speed increases in the same proportion. In practice, this makes the choice of pulley size important because it affects both the speed and the resolution of the axis. A larger pulley gives more travel per revolution and therefore higher linear speed, while a smaller pulley gives finer displacement but lower maximum speed.[76]

The torque generated by the motor is transmitted to the belt through the pulley. As the pulley rotates, it applies a tangential pulling force to the belt teeth, which then moves the carriage. The relationship between torque and the belt force can be expressed as

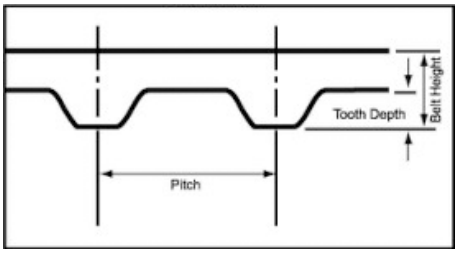
$$T = \frac{F_t\, r}{2000}$$

where T is the motor torque, F_t is the tangential force applied to the belt, and r is the pulley radius. This relation shows that for a given required linear force on the carriage, a larger pulley requires higher motor torque, while a smaller pulley reduces the torque demand but also reduces the linear travel per revolution.For this reason, pulley size influences not only speed and resolution, but also the mechanical effort required from the motor.[42]

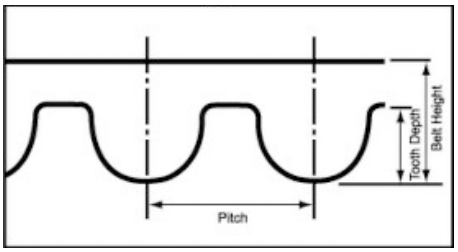
Belt tension is also a critical parameter. The belt must be pre-tensioned enough to keep the teeth fully engaged with the pulley and avoid backlash or tooth skipping under load. If the belt is too loose, the carriage may lose positional accuracy, the motion may become less stable, and the drive may slip under sudden load changes. If the belt is too tight, the system can create unnecessary friction, increase bearing load, and raise the torque required from the motor. The correct tension is therefore a balanced condition: firm enough to ensure accurate transmission, but not so high that

it overloads the drive components. [112]

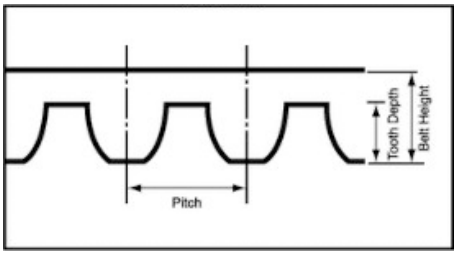
Another important characteristic of timing belt drives is the tooth profile, since it affects smoothness, repeatability, wear, and force transmission. Trapezoidal teeth are the simplest profile and can transmit significant force, but they tend to produce more noise, more abrupt engagement, and faster wear because the contact is more concentrated at the belt-pulley interface, as shown in Figure II.10 (a). Curvilinear teeth, such as HTD profiles, were developed to reduce stress concentration and improve power handling, which makes the motion smoother and the load distribution more uniform, as shown in Figure II.10 (b). Modified curvilinear profiles go a step further by improving load sharing between the engaged teeth, which helps improve motion quality, as shown in Figure II.10 (c). For this reason, the tooth profile is an important selection criterion when choosing a timing belt drive for a CNC axis.[112, 33]



(a) Trapezoidal-shaped teeth



(b) Curvilinear-shaped teeth



(c) Modified curvilinear teeth

Figure II.10: Belt teeth shapes

- **Advantages:** Inexpensive, high velocity and acceleration with light loads, widely available and simple construction.[112]

- **Drawbacks:** Lower stiffness and lower positioning precision than screw-based systems, with some compliance due to belt elasticity.

- **Suitability:** Suitable for light CNC axes, fast positioning axes, and long travel motion where moderate precision is acceptable.[23]

- **Lead screw actuators**

  - **Description:** A lead screw actuator is a linear transmission system that converts the rotary motion of a motor into a controlled translational motion along the machine axis. In this type of design, the motor is connected to

the screw through a coupling, which transmits torque while helping to accommodate small alignment errors between the motor shaft and the screw shaft. The screw is supported by bearings according to the actuator layout, while the nut is constrained by the carriage so that it cannot rotate freely, as shown in Figure II.11. When the screw rotates, the helical thread forces the nut to move along the screw axis, and this linear displacement is transferred to the carriage and then to the moving axis of the CNC machine. In other words, the rotation of the motor is progressively transformed into a straight-line movement through the screw-thread contact.[106, 61]

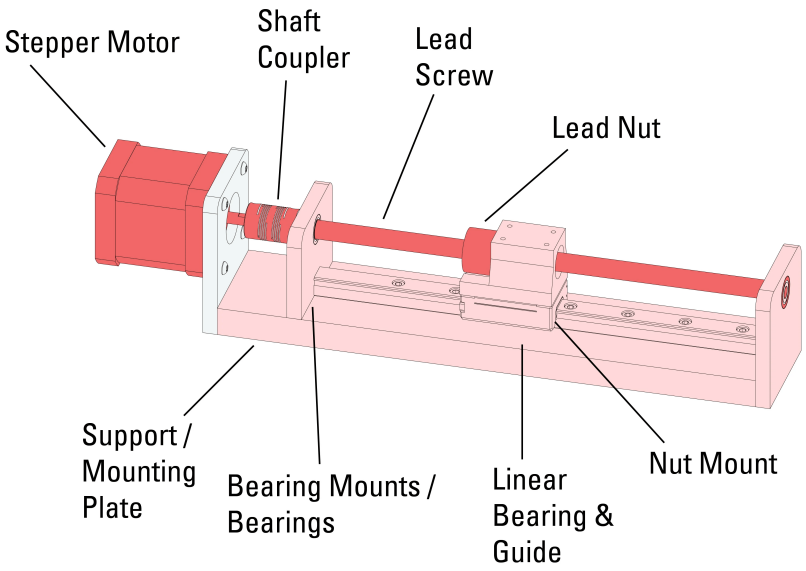
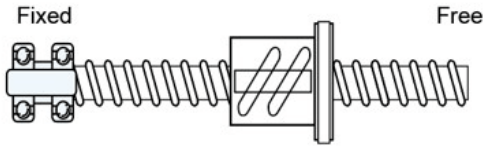


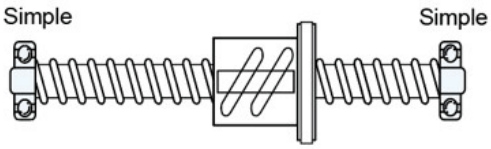
Figure II.11: Lead screw drive

The general layout of the actuator can be arranged in different support configurations (end fixity), such as fixed-free, floating-floating, fixed-floating, and fixed-fixed. In a fixed-free arrangement, one end of the screw is driven while the other end is left unsupported, as shown in Figure II.12 (a), which keeps the design simple but limits the allowable speed and load. In a floating-floating (simple-simple) arrangement, both ends are simply supported by a simple radial bearings, as shown in Figure II.12 (b), which are a standard deep groove ball bearings, that can handle moderate radial loads (forces acting perpendicular to the shaft), they quickly fail when subjected to heavy axial forces(forces acting parallel to the shaft), this bearing arrangement has the benefit of easy mounting while still providing radial support for the screw. A fixed-floating (fixed-simple) arrangement is probably the most common type of end fixity, both ends are supported by bearings, as shown in Figure II.12 (c), but a thrust bearing (specifically designed bearings to support massive axial loads) only at one, which improves stability compared with the free-end case. In a fixed-fixed arrangement, both ends are highly supported, as shown in Figure II.12 (d), which increases the highest speed capability and provides maximum rigidity, but it doesn't allow any axial movement of the screw in the case of thermal expansion. The choice of arrangement influ-

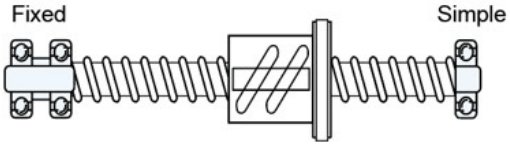
ences the critical speed, stiffness, and overall accuracy of the actuator, so it must be selected according to the required travel length and operating conditions.[29, 30, 61, 108]



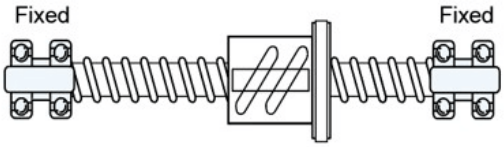
(a) Fixed-free configuration



(b) Floating-floating configuration



(c) Fixed-floating configuration



(d) Fixed-fixed configuration

Figure II.12: Lead screw support configuration

The transmitted motion is ruled by the thread geometry. The lead L represents the axial distance traveled by the nut during one full revolution of the screw, which is equal to the pitch p (linear distance between two adjacent thread peaks) for a single start screw.The number of starts refers to the number of threads that are wrapped around the axis of the lead screw. Each thread has its own starting point and is visible by looking at the end of the shaft, as shown in Figure II.13. When a lead screw has more than one start, it is referred to as a multi-start lead screw, while for a multi-start screw, the lead becomes larger according to the number of starts n:

$$L = n\,p$$

This relation is important because it directly links the screw geometry to the linear speed and positioning resolution of the axis. A smaller lead produces finer displacement steps and higher mechanical advantage, while a larger lead allows faster movement but reduces the thrust that can be obtained for the same motor torque.[61, 112, 6]

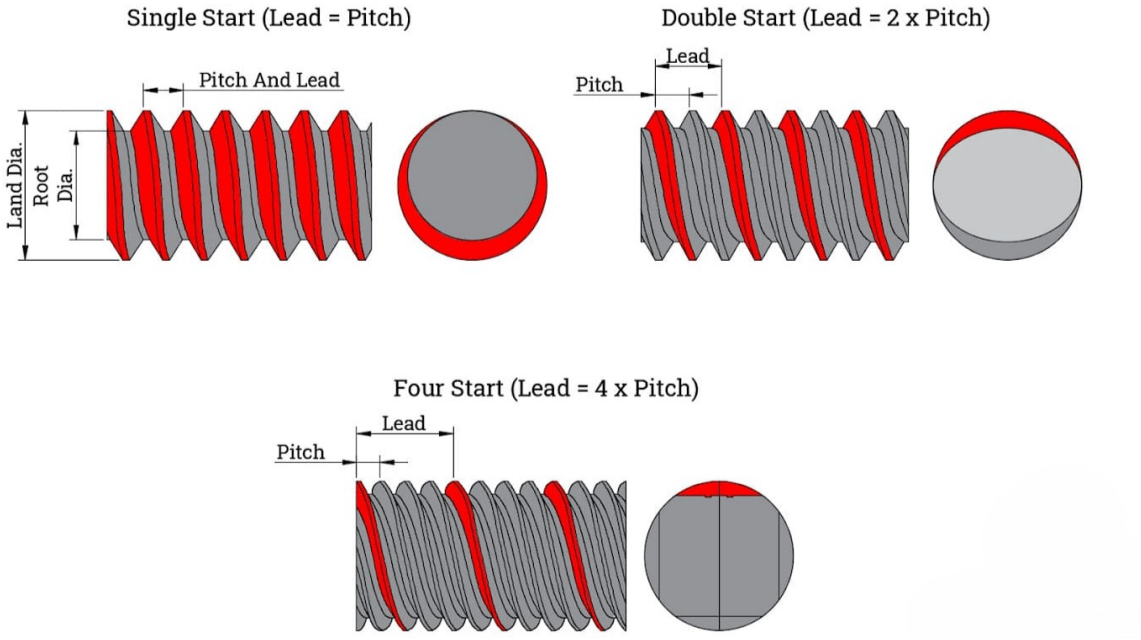
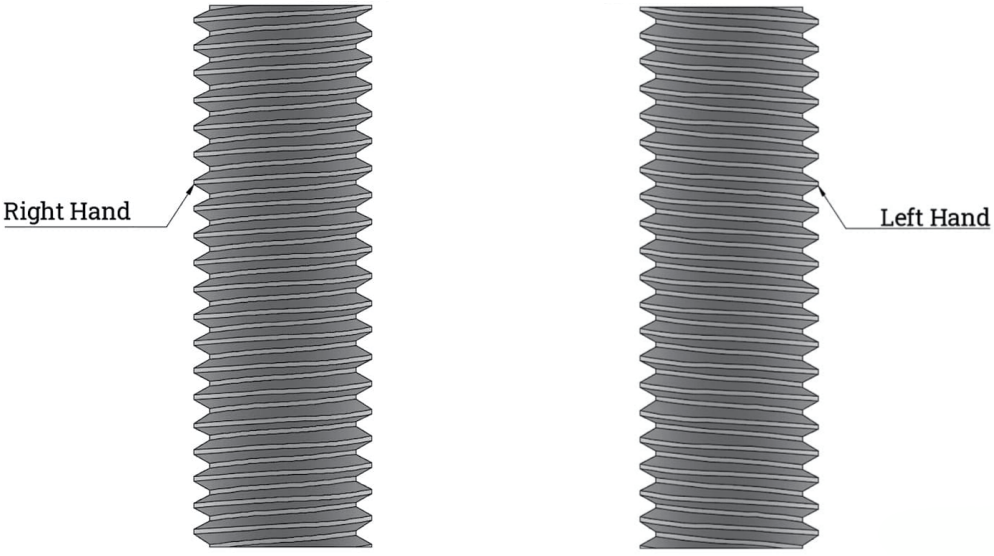


Figure II.13: Relationship between pitch, lead, and number of starts

The handedness of the thread, left-hand (as shown in Figure II.14 (b)) or right-hand (as shown in Figure II.14 (a)), determines the direction of the axial motion for a given direction of rotation, which is why thread orientation must be chosen according to the intended machine kinematics. [61]

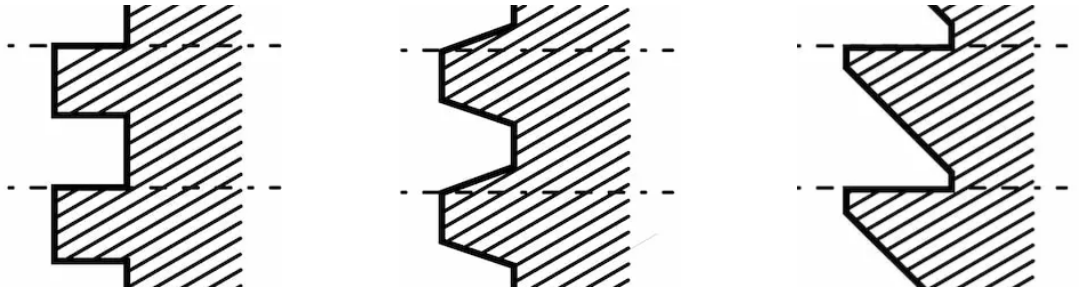


(a) Right hand (b) Left hand

Figure II.14: Handedness of the threads

Lead screws are also classified according to their thread form, such as square, acme, and buttress threads. The square thread has square-shaped threads whose flanks are perpendicular to the axis of the lead

screw. This 0° thread (As shown in Figure II.15 (a)) angle prevents any radial pressure on components and reduces friction by minimizing the contact surface between the nut and the screw. Thus, square threads have the lowest friction losses and the highest efficiency, but they are the most difficult and expensive to manufacture. Acme or trapezoidal threads (As shown in Figure II.15 (b)) are more common in general power transmission because they are easier to produce and offer a good compromise between strength, wear resistance, and manufacturability. Buttress threads are mainly used when the load is strongly transmitted in one axial direction, since their asymmetrical profile (As shown in Figure II.15 (c)) is better suited to unidirectional thrust. For this reason, the thread form is not only a geometric detail but also a design choice that affects efficiency, strength, and practical use. [61, 106]



(a) Square (b) ACME (c) buttress

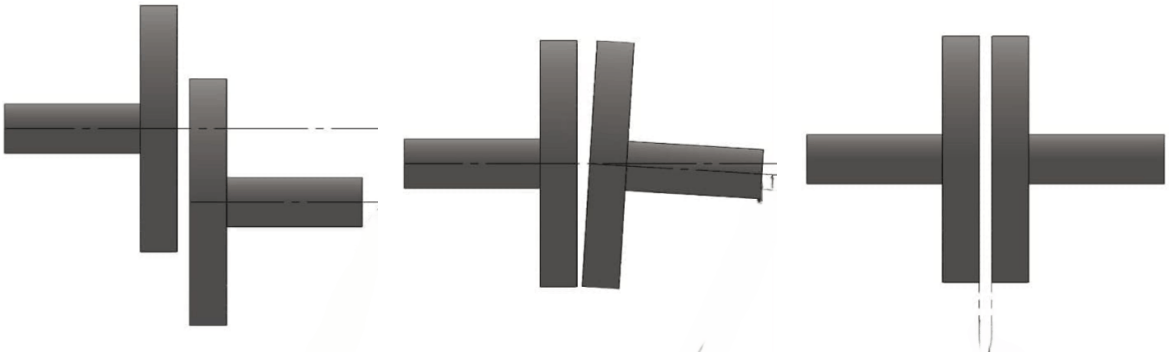
Figure II.15: Lead screw thread form

The nut plays an equally important role in the transmission system. A standard nut provides the sliding interface with the screw, while an anti-backlash nut is used when higher repeatability is required. In an anti-backlash design, the axial clearance between the screw and the nut is reduced by preloading two nut halves or by applying a spring force (As shown in Figure II.16)between them, which helps remove free play during direction changes. This improves positioning accuracy, but it also increases drag and may limit the allowable load if the preload becomes too high. [112, 61]



Figure II.16: Anti-backlash nut

One of the other important factors for lead screw actuators is the shaft coupling chosen, as it serves as the primary mechanical interface for transmitting rotational power from a driving source, such as a motor, to a driven component like a lead screw. Beyond facilitating torque transfer, its critical function is to accommodate misalignment (the geometric offset between shaft centers) which can manifest as lateral (Figure II.17 (a)), angular (Figure II.17 (b)), or axial deviations (Figure II.17 (c)). By compensating for these offsets, the coupling prevents operational issues such as excessive noise, vibration, and accelerated bearing wear, while simultaneously acting as a dampening element to absorb mechanical impacts and protect the drive's long-term structural integrity.[112, 96]



(a) Lateral misalignment (b) Angular misalignment (c) Axial misalignment

Figure II.17: Shaft misalignments

- **Advantages:** Simple construction, good positioning resolution, high thrust at low speed, compact design, low cost for small and medium axes.[112, 23]

- **Drawbacks:** Lower efficiency due to sliding friction, backlash if no preload is used, wear over time, limited maximum speed, and higher torque demand for large leads or heavy loads.[112, 23]

- **Suitability:** Suitable for low-to-moderate speed CNC axes, compact machines, prototype systems, and axes where precision is more important than very high travel speed.

- **Ball screw actuators**

  - **Description:** A ball screw actuator is a linear transmission system closely related to the lead screw actuator, but with a different method of force transmission between the screw and the nut. As in the case of the lead screw, the motor is connected to the screw through a coupling, and the screw is supported by bearings according to the actuator layout. The rotation of the motor is then transferred to the screw, and the screw motion is converted into a linear motion of the nut and the carriage, as shown in Figure II.18. However, the main difference is that the contact between

the screw and the nut is not based on direct sliding. Instead, the load is transmitted through steel balls that roll inside the grooves of the screw and the nut, then return through an internal circulation path to complete continuous motion. This rolling principle greatly reduces friction and allows the actuator to achieve high efficiency, low driving torque, and smoother motion than a conventional lead screw. In this sense, the ball screw keeps the same basic mechanical function as the lead screw, but improves its dynamic behavior by replacing sliding contact with rolling contact.[85, 60]

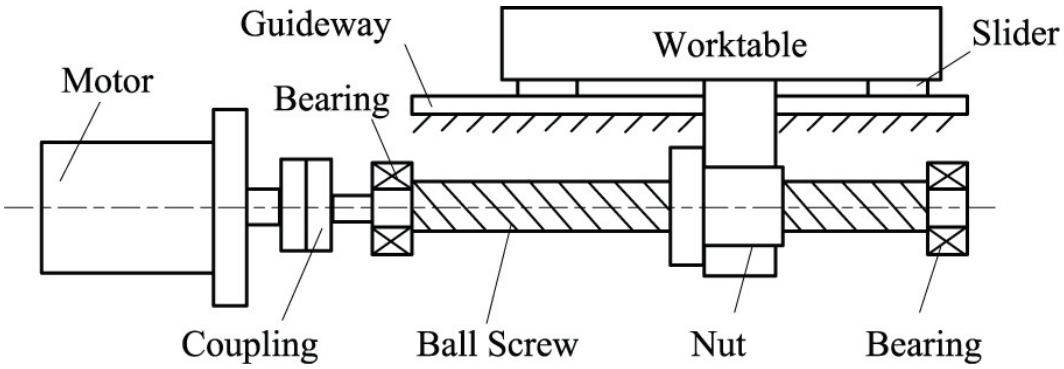


Figure II.18: Ball screw drive

Beyond the internal drive mechanics, the shaft support arrangement is vital to the actuator's overall stability. As detailed in **lead screw actuator layout**, the end-fixity condition directly governs the system's stiffness, vibrational limits, and maximum rotational speed. For ball screw applications, optimizing these support bearings is particularly critical because these axes frequently operate at higher velocities.

The geometric performance of the ball screw actuator remains fundamentally governed by the same principles of **the lead**, **the number of starts**, and **the handedness** of the thread. As detailed in the earlier discussion regarding lead screw parameters, these core attributes dictate the axial displacement per revolution and the resulting direction of travel.

While external support structures govern the broader kinematic limits of the axis, the internal groove geometry remains the defining factor for the actuator's core precision. High-precision systems utilize a gothic-arch profile, which offers superior contact mechanics compared to a standard circular groove. This specialized shape facilitates a distinct two-point contact between the rolling elements and the raceways, as shown in Figure II.19, ensuring that mechanical loads are distributed more uniformly while significantly enhancing axial rigidity.[60]

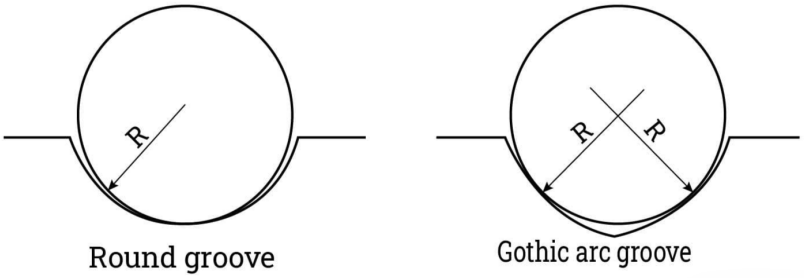


Figure II.19: Ball groove profiles

Equally important to the thread's internal geometry is how it is produced. The manufacturing process of the screw shaft (either precision grinding or rolling) determines the final accuracy and application suitability of the actuator. A precision-ground shaft is manufactured to extremely tight geometric tolerances, offering superior lead consistency and smooth operation for high-end industrial machines, as shown in Figure II.20 (a). In contrast, a rolled shaft is produced through a cold-forming process, providing a more economical solution for general-purpose automation, as shown in Figure II.20 (b). The choice between these methods involves a balance between the required accuracy class, the expected duty cycle, and the overall budget of the project.[60, 68, 35]

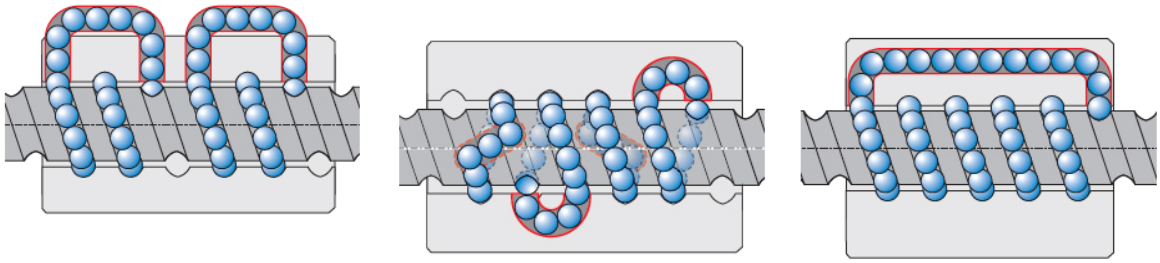


(a) Ground shaft (b) Rolled shaft

Figure II.20: Ball screw shaft

The nut assembly serves as the primary differentiator between the ball screw and the conventional lead screw by facilitating a transition from sliding friction to high-efficiency rolling contact. This transformation is achieved through a continuous recirculation system. As the screw rotates, the load-bearing balls exit the active contact zone and are routed through a dedicated return circuit to their starting position, ensuring an uninterrupted flow of rolling elements during linear translation. The specific architecture of this recirculation path is typically categorized into three main designs, each optimized for different operational constraints. The return-pipe type utilizes an external tube to guide balls over the nut body, as shown in Figure II.21 (a), providing a robust and reliable solution for standard industrial applications. In contrast, the deflector type employs internal elements to redirect balls within a significantly smaller spatial

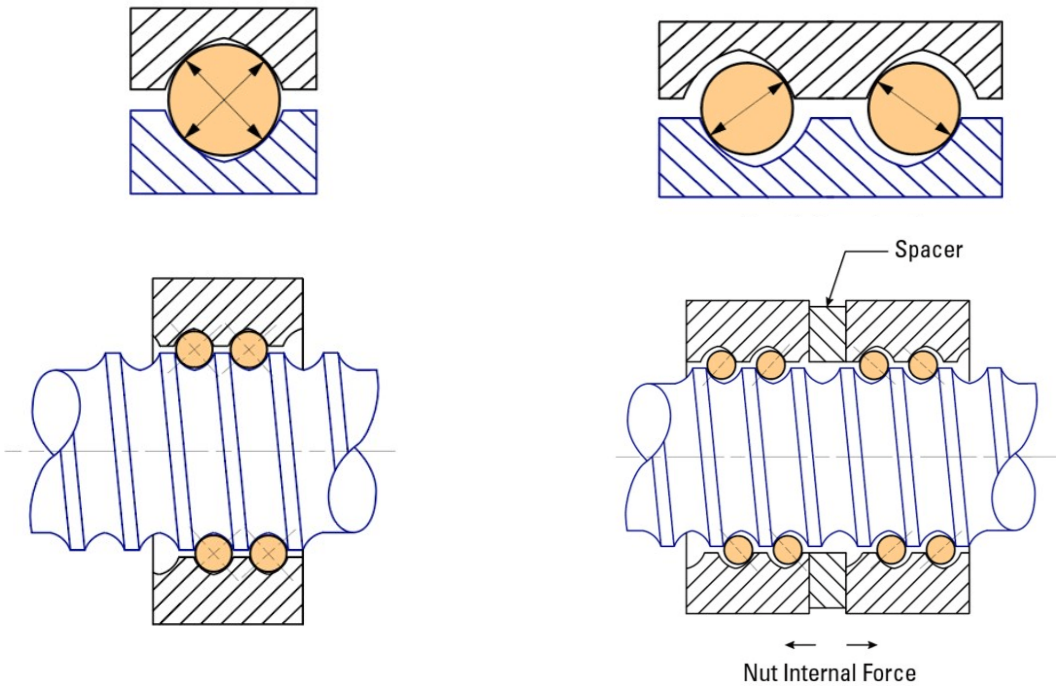
envelope, as shown in Figure II.21 (b), making it ideal for compact machine designs. Finally, the end-cap type routes the balls through passages integrated into the nut's longitudinal ends, as shown in Figure II.21 (c), which minimizes vibration and ensures the stability required for the high-velocity movements characteristic of modern CNC axes.[60, 28, 65]



(a) External tube recirculation (b) Deflector recirculation (c) End cap recirculation

Figure II.21: Ball nut recirculation systems

Preloading is an essential design feature in ball screw actuators, serving to eliminate axial clearance and backlash during motion reversals, therefore enhancing the overall rigidity of the transmission. This can be done by applying a controlled internal force to the rolling elements, which ensures continuous contact between the balls and the raceways, maintaining positioning accuracy. This internal tension can be achieved through several distinct mechanical strategies, each offering different performance characteristics regarding stiffness and thermal stability. One common approach is the oversized ball method, the rolling elements are manufactured with a diameter slightly larger than the space between the screw and nut grooves, which creates a strategic interference that results in a four-point contact geometry, as shown in Figure II.22 (a), effectively removing play while maintaining a compact and cost-effective footprint, This method is generally less rigid than the common double-nut arrangement. It consists of two separate nuts bridged by a precision spacer, as shown in Figure II.22 (b). By adjusting the spacer's thickness, the nuts are forced in opposite directions along the screw to create a fixed-point preload. This setup provides exceptional axial rigidity and consistent repeatability, although it is more sensitive to the thermal expansion of the screw shaft. Alternatively, a double-nut arrangement using springs instead of a rigid spacer solves this issue. This method is particularly beneficial for systems operating over a wide temperature range, as the springs can compensate for small changes in screw length without significantly altering the preload intensity. However, this flexibility comes at the cost of lower overall axial stiffness compared to the spacer method. Elastic elements, such as coil or wave springs, placed between the nuts, do maintain a nearly constant internal force. Ultimately, selecting the appropriate preloading technique is critical, as it can impact the long-term durability of the actuator.[60, 105, 32]



(a) Oversized ball bearing arrangement (b) Double nut arrangement

Figure II.22: Preloading arrangement

Consistent with the mechanical principles detailed in the earlier discussion on **shaft couplings**, this component fulfills the same critical role within a ball screw actuator. It serves as the primary mechanical interface, efficiently transmitting motor torque while actively compensating for inevitable geometric misalignments between the drive and driven shafts, which is essential to prevent bearing fatigue and to maintain the stable power transmission required for accurate multi-axis machining.

- **Advantages:** High efficiency, low driving torque, high rigidity when preloaded, low backlash, smooth motion, good repeatability.[84, 112]

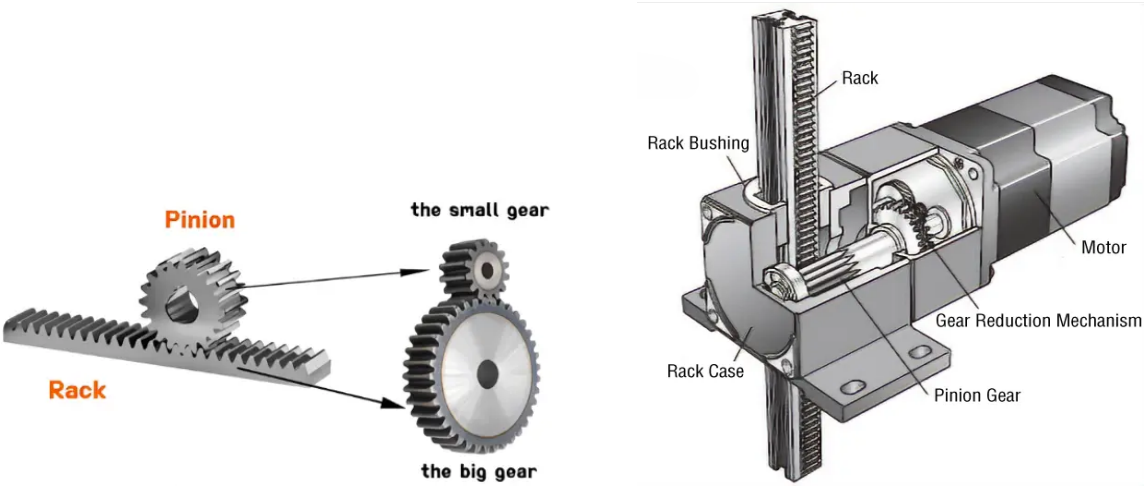
- **Drawbacks:** Higher cost than lead screws, more sensitive to contamination and lubrication, preload increases assembly complexity, allowable speed depends on shaft support, and critical speed.[84]

- **Suitability:** Suitable for precision CNC axes, high-repeatability motion, and higher feed speeds. Appropriate when accuracy, stiffness, and dynamic performance are more important than low cost.

- **Rack and pinion actuators**

  - **Description:** A rack and pinion drive is a linear transmission system that converts rotary motion into linear motion through the meshing of a circular gear, called the pinion, with a linear toothed element, named the rack. The pinion is the driving gear, with a small pitch diameter and

few teeth, while the rack can be understood as the developed form of a larger gear, as shown in Figure II.23 (a). The motor rotates the pinion, and the meshing teeth transmit the force to the rack, which then moves along the axis length, as shown in Figure II.23 (b). In many machine designs, a gearbox is placed between the motor and the pinion. The gearbox reduces the motor speed and increases the output torque, so the pinion can generate the required linear force without forcing the motor to operate outside its preferred speed range. In systems where the motor already provides sufficient torque, a direct drive connection can be preferred because it reduces mechanical complexity and avoids adding extra backlash from the reducer. [34, 14, 112]



(a) Gears mesh to racks and pinions (b) Rack and pinion drive

Figure II.23: Rack and pinion

The layout of the actuator can also vary according to the machine architecture. In one common configuration, the rack is fixed to the machine structure, and the pinion, motor, and gearbox move with the carriage. This layout is often preferred for long axes because the rack remains stationary while the moving mass is limited to the drive unit. In the opposite configuration, the drive unit is fixed, and the rack moves with the loaded mechanism. This solution is less common, but it can be useful when the machine design or the loading conditions make the moving rack more practical.[40, 12]

Unlike a screw drive, a rack and pinion does not use a lead in the screw sense. The pinion pitch circle determines the equivalent linear advance per pinion revolution, so one full revolution produces a linear travel equal to the pinion circumference:

$$x_{\text{rev}} = \pi d_p = z_p \, p_c$$

where x_{rev} is the linear displacement per pinion revolution, d_p is the pitch diameter, z_p is the number of teeth, and p_c is the circular pitch, as shown in

Figure II.24. If a gearbox with a reduction ratio i is used, the linear travel per motor revolution becomes:

$$x_{\text{motor rev}} = \frac{\pi d_p}{i}$$

This relation shows that a smaller pinion or a larger reduction ratio require higher rotational speed to achieve the same linear travel, but they reduce the torque demand and can help limit backlash effects, while a larger pinion covers more distance per revolution but requires more torque to provide the same force and reduce the mechanical advantage. For this reason, the pinion size must be selected together with the motor speed, gearbox ratio, and required axis feed rate.[34, 40, 39, 14]

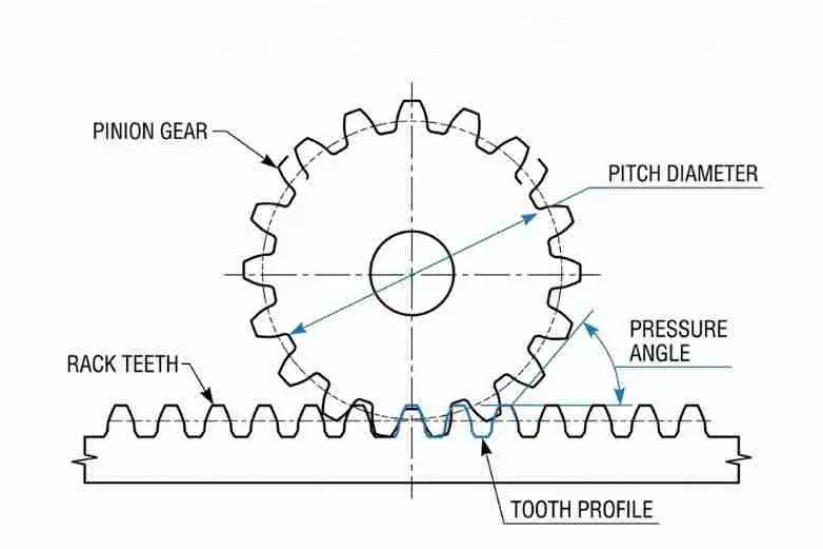
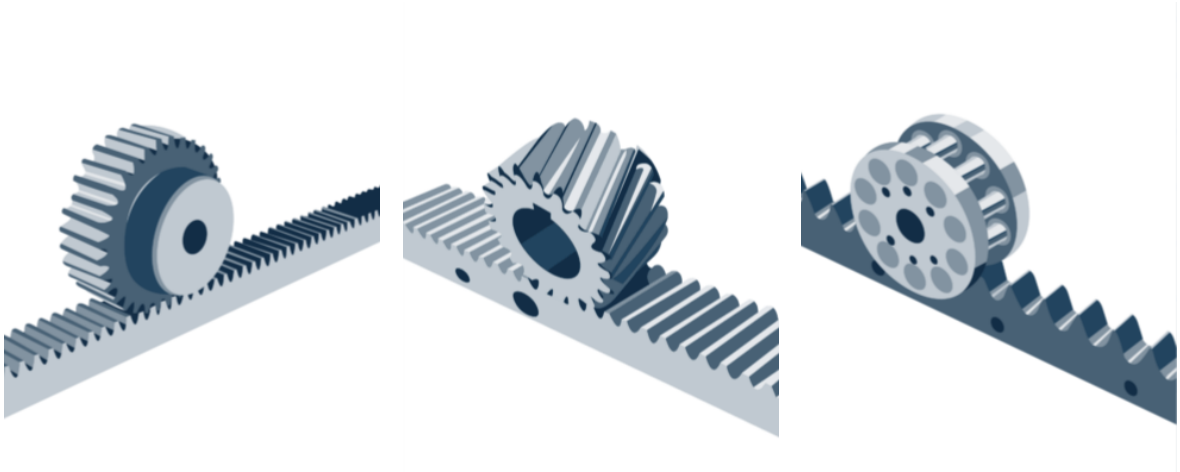


Figure II.24: Rack and pinion drive components

The rack is commonly available with straight or helical teeth, and each requires a matching pinion geometry. Straight racks have teeth parallel to the axis of motion, and they are paired with straight-tooth pinions, as shown in Figure II.25 (a), which makes the system simpler to manufacture, easier to align, and easier to assemble. Helical racks have teeth inclined to the axis, and they require helical pinions with the same helix geometry, as shown in Figure II.25 (b), which improves tooth contact ratio and load sharing, leading to smoother and quieter operation. Helical profiles are therefore preferred when higher stiffness and better motion quality are required, whereas straight profiles remain attractive when simplicity and assembly tolerance are more important. Roller rack systems can also be mentioned as an alternative to conventional rack and pinion drives. In this case, the pinion is replaced by a roller-based element with bearing-supported rollers, as shown in Figure II.25 (c), which reduces sliding friction and can significantly improve positional accuracy and repeatability.[14, 31]



(a) Straight rack (b) Helical rack (c) Roller rack

Figure II.25: Types of rack and pinion gear sets

Backlash is one of the main factors that limits positioning accuracy in rack and pinion drives. Because the teeth must retain a small clearance for smooth meshing, a small amount of free play can appear during direction reversal, especially if the system is poorly aligned. To reduce the effect of backlash, preload can be introduced by means of a split pinion, a dual-pinion arrangement, or another anti-backlash mechanism that keeps both flanks of the tooth contact engaged. These solutions improve repeatability, but they also require more careful adjustment and can increase mechanical complexity.[31, 22]

Rack and pinion drives are especially attractive for long strokes because their travel length is not limited by a screw length in the same way as screw-based actuators, as shown in Figure II.26. This makes them suitable for large-span axes and gantry-type machines where long travel and moderate-to-high speed are required. Their open contact, however, makes lubrication an important design and maintenance issue. Proper lubrication reduces wear, limits noise, and improves the consistency of meshing over time, while poor lubrication can increase friction and reduce service life. In this sense, rack and pinion systems are robust, but they must still be assembled and maintained carefully if stable accuracy is desired.

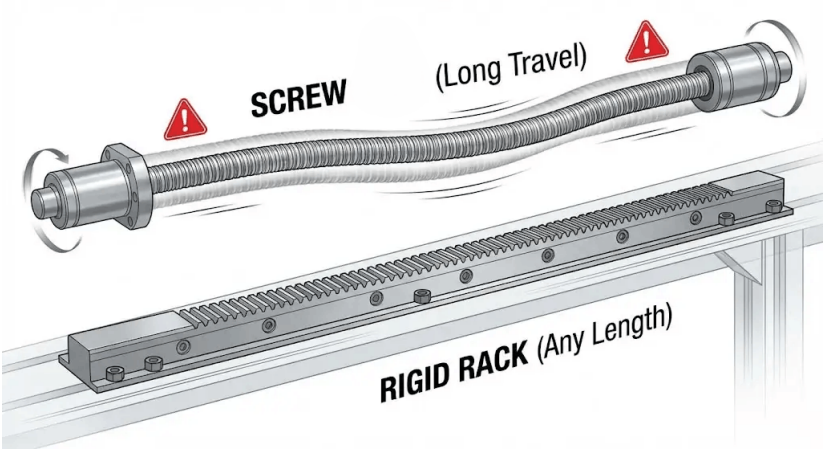


Figure II.26: Ball screw vs rack and pinion drive length

- **Advantages:** Long travel capacity, high load transmission, compact mechanism, good dynamic response, suitable for large axes and high-speed motion. [112]

- **Drawbacks:** Backlash between meshing teeth, lower positioning accuracy than screw drives unless preload is used, lubrication and alignment are important, open transmission requires maintenance.[112]

- **Suitability:** Suitable for long CNC axes, gantry systems, and large machines where travel length, speed, and load capacity are more important than very fine screw-level positioning.

Among the linear motion actuators discussed in this section, each solution presents a different balance between speed, accuracy, stiffness, and load capacity. As illustrated in Figure II.27, the timing belt drive corresponds to the lower end of the performance range, while the ball screw represents the highest level of precision and rigidity. The lead screw and rack and pinion systems occupy intermediate positions, depending on the required travel length and operating conditions. This classification is indicative, since the most suitable transmission system depends on the machine architecture and the expected duty of the axis.

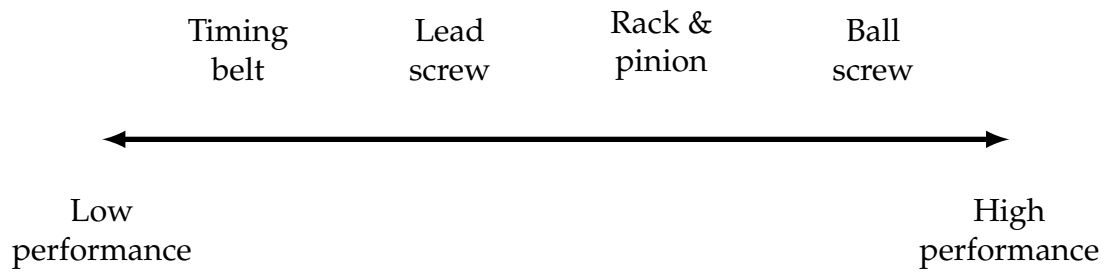


Figure II.27: Classification of linear motion actuators according to performance

II.3.1.4 Rotational transmission systems

Rotational transmission systems are used to control angular position and transmit torque in the rotary axes of a CNC machine. These axes may be integrated either in the head or in the table, and the choice of transmission depends on the required **specifications**. In all of these systems, the purpose is not to convert rotation into translation, as in the linear actuator, but to transmit rotation while adapting the relationship between speed, torque, inertia, and angular resolution to the requirements of the axis. In general, some solutions are more suitable for compact head-mounted configurations, while others are more appropriate for heavier rotary tables or indexing units. The following systems are therefore presented from simpler arrangements to more specialized solutions, starting with the timing belt drive.

- **Timing belt drives in rotary axes**
  - **Description:** In a rotary axis, a timing belt drive transmits angular motion between the motor and the output shaft through a closed synchronous belt and two toothed pulleys. The belt remains in continuous mesh with the pulleys, ensuring a positive transmission that does not rely solely on friction, as shown in Figure II.28. The rotary shaft is commonly supported by preloaded bearings, and in compact rotary stages, duplex angular-contact bearings are often used because they can carry combined axial and radial loads while improving rigidity and reducing run-out. This configuration is ideal when the motor must be placed away from the rotating part or when the rotary head must remain as light and compact as possible. [115]

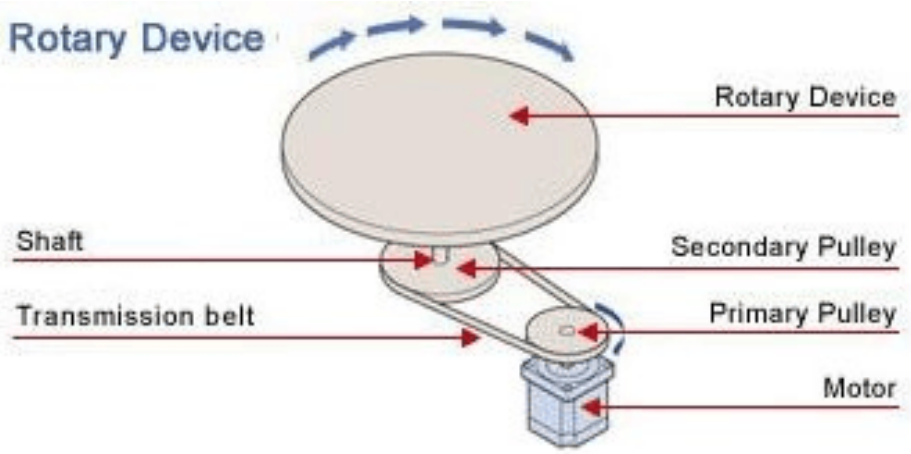


Figure II.28: Timing belt rotational transmission drive

Building upon the mechanical behavior of the belt, the kinematic performance of the rotary axis is primarily governed by the transmission ratio established between the driving and driven pulleys. This ratio is defined by the number of teeth on each pulley and directly relates the input motion to the output motion, and can be expressed as

$$i = \frac{N_2}{N_1} = \frac{\omega_1}{\omega_2}$$

where N_1 and N_2 are the number of teeth on the driving and driven pulleys, and ω_1, ω_2 are their angular velocities. The driving pulley, mounted on the motor shaft, supplies the input torque, while the driven pulley transfers the corresponding motion to the output shaft.[115]

When a reduction configuration is used, where the driving pulley has fewer teeth than the driven pulley, the output shaft rotates more slowly, but the transmitted torque is increased. At the same time, the angular displacement produced at the output for each motor increment is reduced, which improves the effective angular resolution of the axis and allows finer positioning. [115]

Conversely, when the driving pulley is larger than the driven pulley, the system operates in a speed-increasing configuration. In this case, the output shaft rotates faster, but the available torque is reduced, and each motor increment produces a larger angular displacement at the output, which decreases positioning resolution. This configuration is therefore more suitable when a high rotational speed is required, and the load is relatively low.[115]

Beyond the geometric parameters of the pulley, the overall performance of the transmission is fundamentally governed by the mechanical characteristics of the timing belt itself. Critical factors such as the applied installation **tension** and the specific **tooth profile** are essential for minimizing backlash, and ensuring efficient power transfer.

- **Advantages:** Simple construction, flexible layout, remote motor placement. [100]

- **Drawbacks:** Lower torsional stiffness, belt compliance can reduce positioning quality under load, tension must be maintained, accuracy depends strongly on belt condition and assembly quality.

- **Suitability:** Suitable for head-mounted rotary axes when compactness, reduced moving mass, and moderate accuracy are more important than maximum rigidity. It is also suitable for indexing units and auxiliary rotary modules where a simple and economical solution is preferred.

- **Harmonic drive actuators**

  - **Description:** A Harmonic Drive is a unique type of gear reducer. At the heart of this drive system lies a clever mechanism that uses flexible motion and strategic tooth engagement to achieve exceptional precision. The system consists of three core components: the wave generator, the flexible spline (flexspline), and the circular spline, as shown in Figure II.29. [113]

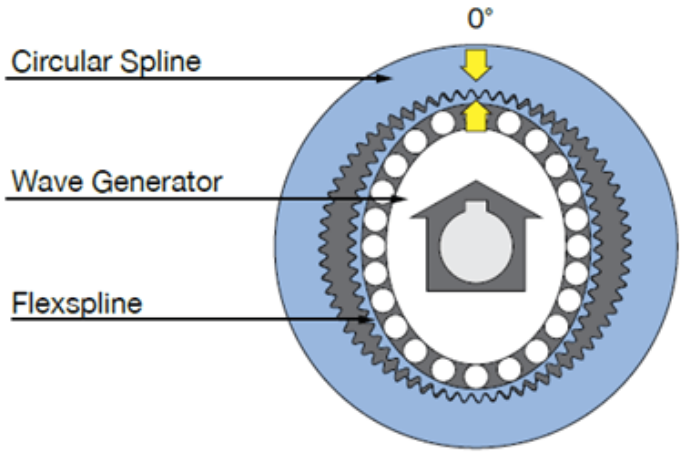


Figure II.29: Harmonic drive components

The wave generator is an elliptical cam fitted with a bearing, which deforms the thin, cup-shaped flexspline into an elliptical form as it rotates. This deformation causes the flexspline teeth to engage the internal teeth of the circular spline at two opposite regions of contact. The reduction mechanism results from the small difference in tooth count between the two elements, the flexspline typically having two fewer teeth than the circular spline. Consequently, each full revolution of the wave generator produces a small relative displacement between the two gears, leading to a high reduction ratio, as shown in Figure II.30. For instance, a circular spline with 162 teeth and a flexspline with 160 teeth yields a ratio of 80:1. The reduction ratio of a harmonic drive is commonly expressed as

$$i = \frac{N_f}{N_f - N_c}$$

where N_f and N_c are the numbers of teeth on the flexspline and circular spline, respectively. This ratio can be modified either by changing the mechanism diameter while keeping the same tooth size, or by adjusting the tooth size while preserving the overall size and mass of the gear set, increasing the number of teeth in both cases. As a result, this configuration enables very high torque multiplication in a compact volume, near-zero backlash, and smooth torque transmission, which are particularly advantageous in precision motion control applications. [113, 38]

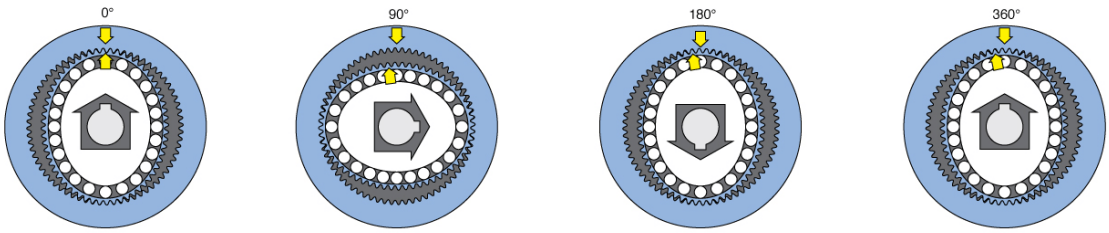


Figure II.30: Harmonic drive motion

  - **Advantages:** Very high reduction ratio in a single stage, extremely low backlash, high positioning accuracy, compact coaxial design, high torque density. [113]

  - **Drawbacks:** Higher cost, more specialized construction, sensitive to assembly tolerances, performance depends on precise alignment, elastic flexspline introduces controlled compliance.

  - **Suitability:** Suitable for high-precision rotary axes, where compactness, fine angular resolution, and high torque multiplication are required.

- **Direct drive**

  - **Description:** A direct drive system is a rotary transmission configuration in which mechanical transmission elements such as gears, belts, or worm drives are completely eliminated, and the motor is coupled directly to the load. In a 5-axis CNC rotary axis, this means that the rotor of the motor is directly attached to the rotating component of the machine head, allowing torque to be transmitted without any intermediate mechanism. This direct coupling significantly simplifies the transmission chain and removes the sources of backlash and compliance typically associated with mechanical reductions. [9, 44]

    To achieve this integration, direct drive systems commonly use a frameless motor architecture composed of a permanent magnet rotor and a copper-wound stator, as shown in Figure II.31. The stator is fixed to the machine structure, while the rotor is mounted directly on the rotating element, such as the spindle support. Since no gearbox is present to provide structural support or guide the motion, the mechanical stability of the axis relies on a dedicated High-precision bearings, such as crossed-roller, that are typically used because they can simultaneously withstand axial, radial, and moment loads generated during machining operations, while maintaining high rigidity and minimal runout, the motor is often designed with a large diameter and a reduced axial length, forming a compact structure. A high-resolution encoder is directly mounted on the rotating shaft to provide accurate position feedback for closed-loop control. [9, 44]

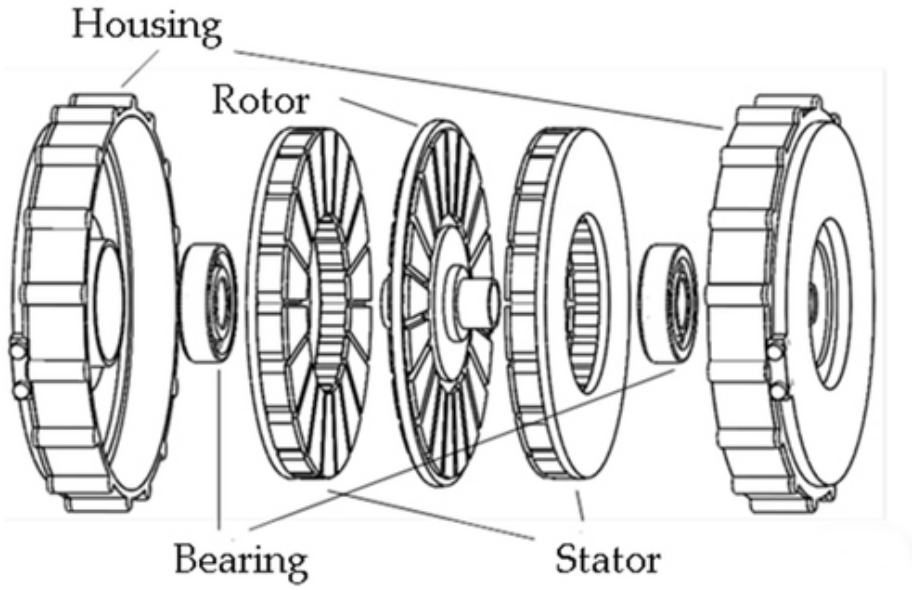


Figure II.31: Direct drive

- **Advantages:** No backlash, high positioning accuracy, high dynamic performance, smooth motion, reduced mechanical complexity, low maintenance requirements. [47]

- **Drawbacks:** Higher cost, demanding motor sizing, strong dependence on control and encoder quality, thermal management required. [47]

- **Suitability:** Suitable for high-precision rotary axes and advanced 5-axis machining centers where maximum accuracy, smooth motion, and dynamic performance are required.

In addition to the previously discussed transmission systems, it is worth mentioning other commonly used rotary drive solutions, such as worm gear drives, planetary gear systems, and bevel gear arrangements. These systems are widely applied in CNC rotary axes due to their ability to provide high reduction ratios, compact transmission layouts, and efficient torque transfer, depending on the required orientation and load conditions. Although they are not examined in detail in this section, they represent important alternatives that may be better suited for specific machine configurations or performance requirements.

II.3.2 Electrical hardware and components selection

The electrical hardware of a CNC machine is not limited to the controller alone, but also includes the drive motors, the feedback sensors, and the power elements required to operate them. Within this architecture, the controller coordinates motion commands, the motor converts electrical energy into mechanical motion, and the sensors provide position and speed feedback so that the machine can maintain

accurate closed-loop control. The selection of these components, therefore, has a direct influence on the dynamics of the machine.

II.3.2.1 CNC controllers

At the core of the CNC's electrical architecture lies the controller, the central processing unit responsible for interpreting commanded toolpaths and orchestrating the synchronized movement of the machine axes. Because this component dictates the ultimate precision, processing speed, and integration capabilities of the machine, selecting the appropriate hardware is a critical design step. Consequently, this section evaluates the spectrum of available control methodologies, ranging from basic microcontroller-based systems to advanced industrial platforms, to establish a framework for determining the optimal solution for the prototype.

II.3.2.1.1 Industrial controllers

Industrial CNC controllers represent the highest level of control integration in the CNC hierarchy. They are standalone hardware systems with dedicated real-time processing capabilities. They connect and run hardware, software, and peripherals, and are designed to interpret G-code, generate motion commands, and coordinate synchronization between the machine axes without relying on a separate PC for basic motion execution. These controllers are used in industrial CNC machines at the high end of the market and are not common in low-cost or prototypes because they require premium supporting components such as servo drives, limit switches, and other industrial peripherals. [51, 21]

Their main advantage is the level of reliability and integration they provide. Because they are built for industrial use, they offer strong real-time performance, stable axis coordination, and better compatibility with demanding machine-tool applications.

Their drawbacks are mainly the cost and level of system complexity. Industrial controllers are expensive, require compatible high-quality subcomponents, and are generally unnecessary for simpler machines where the full performance of an industrial platform would not be used. They also require a more advanced configuration effort, which makes them less accessible for small-scale projects or educational prototypes. [21]

II.3.2.1.2 PC based controllers

A PC-based CNC controller is a control system in which a standard personal computer runs dedicated software to interpret machining programs (G-code) and generate motion commands. In this setup, the PC handles high-level operations such as toolpath interpretation, graphical simulation, and user interface management, while a hardware interface converts these commands into real-time electrical signals (step/dir or servo commands) that drive the motors and interact with sensors. [99, 21, 109]

The most commonly used software packages for this architecture include Mach3,

Mach4, and LinuxCNC. These programs are highly flexible and configurable, allowing users to adapt the control environment to specific machine kinematics. Despite their computational capabilities, these software solutions do not directly interface with motor drivers or sensors. Instead, they rely on intermediary hardware to bridge the gap between the software environment and the physical machine, which is the primary function of the breakout board (BOB).[20, 109]

A CNC breakout board serves as the physical interface between the computer's control signals and the machine's electrical hardware. It distributes, conditions, and isolates the electrical signals exchanged between the PC and the motor drivers. In practice, the breakout board organizes the controller outputs into structured terminals, facilitating the connection of inputs such as limit switches and emergency stops, and outputs such as spindle control and auxiliary devices. In addition, many breakout boards provide electrical isolation, typically through optocouplers, which protects the computer from voltage spikes and electromagnetic interference generated by the machine, thereby improving signal reliability and system safety.[109]

Historically, the most common type of breakout board utilizes the PC's parallel port (LPT), where signals are directly mapped to output terminals for point-to-point wiring. While this approach is simple and cost-effective, it is limited by the timing constraints of the parallel interface and the declining availability of such ports on modern computers. As a result, more recent systems rely on USB or Ethernet interfaces. In these configurations, it is important to distinguish between simple breakout boards, which only provide signal routing, and advanced motion controllers, which include embedded processing and generate precise timing signals independently of the PC.[20, 109]

A key advantage of PC-based control systems is their accessibility and cost-effectiveness. By relying on standard computing hardware, they provide a high level of computational capability and a user-friendly interface without the cost associated with industrial controllers. The use of graphical interfaces and configurable software also facilitates program visualization, parameter adjustment, and system customization.[67]

However, these systems present limitations in terms of real-time reliability. Standard operating systems are not inherently designed for deterministic real-time control, and background processes or system interruptions can affect the timing consistency of motion signals. Additionally, a conventional PC requires more physical space and is more sensitive to environmental conditions such as dust, vibration, and temperature variations compared to dedicated industrial control units. [20]

Considering these characteristics, PC-based CNC controllers are particularly suitable for academic research, prototyping, and custom machine development. They offer a practical balance between flexibility and performance, making them well-suited for experimental configurations such as multi-axis or bi-rotary systems. [99]

II.3.2.1.3 Microcontroller-based controllers

Microcontroller-based CNC controllers represent the simplest control architecture in this classification, and they are typically built around a small embedded board run-

ning dedicated motion-control firmware. In this approach, the firmware is loaded directly onto the microcontroller, and the board itself generates the step-and-direction signals required by the motor drivers while also handling basic machine logic such as homing, feed control, and limit switch management. A common example is GRBL, which is presented as a low-cost alternative to parallel-port-based motion control and is designed to run on a standard Arduino Uno-class board based on the ATmega328P microcontroller. The Arduino Uno provides a compact hardware platform with 14 digital input/output pins and 6 analog inputs, while GRBL is able to maintain stable control pulses at high frequency for small CNC applications. In practice, a separate G-code sender, such as Universal Gcode Sender, is used on the computer side to transmit machining commands to the embedded controller. In this way, the microcontroller performs the real-time motion task, while the computer mainly serves as the programming and supervision interface. [5, 52, 21]

Their main advantage is the combination of low cost, compact hardware, and direct implementation of motion control without the need for a separate industrial controller or a complex PC-based motion interface. This makes them easy to integrate into small machines and well suited to prototyping, educational projects, and hobby CNC systems where a modest number of axes and limited I/O resources are sufficient. [52, 5]

The main drawback is the limited hardware capacity of the microcontroller platform, which constrains the number of inputs and outputs, reduces scalability, and makes the system less suitable for more demanding multi-axis machines. Compared with industrial controllers or more advanced motion-controller architectures, microcontroller-based systems also offer less expansion capability and lower tolerance for complex automation functions. [52, 5]

They are therefore most suitable for small CNC machines, prototype systems, and low-complexity motion applications where affordability, compactness, and simplicity are more important than advanced industrial integration. When the machine architecture becomes more complex or the number of axes increases significantly, a more powerful controller class becomes more appropriate. [52]

II.3.2.2 Drive motors

Drive motors are the electromechanical elements that convert the electrical commands generated by the controller into the mechanical motion required by the CNC axes. Their selection has a direct influence on the available torque, the achievable speed, the positioning accuracy, and the dynamic response of the machine. In practice, the two most common motor families used in CNC systems are stepper motors and servo motors, which occupy different positions in the range from simple open-loop positioning to high-performance closed-loop motion control.

- **Stepper motors**
  - **Description:** Stepper motors are brushless DC electromechanical devices, as shown in Figure II.32, that convert the electrical pulses generated by the controller into discrete mechanical displacement, offering precise control

over position, speed, and torque. Unlike other motors that rotate continuously, stepper motors move in small steps with each input pulse. Since the controller can send a known number of pulses, the exact angular position of the shaft can be obtained deterministically through pulse accumulation, where each pulse corresponds to a specific angular increment known as the step angle, resulting in repeatable, accurate movements without needing complex feedback systems (open-loop configuration). The number of steps per revolution depends upon the motor's design. The common step angles of the stepper motor range from 0.9° to 1.8°, i.e., 200 to 400 steps per revolution. However, unlike servo motors, they may lose synchronization at very high speeds or under heavy loads if not properly managed. [71, 80, 50, 37]

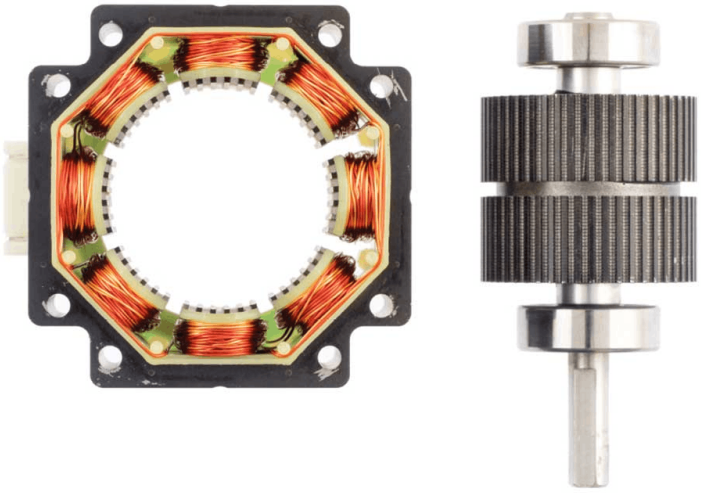


Figure II.32: Stepper motor construction

– **Working principle:** Like all electric motors, stepper motors have a stationary part (the stator) and a moving part (the rotor). On the stator, there are teeth (windings) on which coils are wired, while the rotor is designed to align itself precisely with the magnetic poles generated by the stator. Rather than rotating freely. The fundamental operation of a stepper motor relies on the sequential excitation of stator phases to create a rotating magnetic field. When current flows through a specific stator winding, it generates an electromagnetic pole that exerts a torque on the rotor, forcing it to align its own magnetic poles with the energized stator teeth. By switching the power supply between different phases in a precise chronological order, the rotor is compelled to follow the shifting magnetic flux, advancing in discrete angular increments. This synchronization allows for exact positioning, as the rotor essentially locks into a state of equilibrium with the active magnetic field at each step. As illustrated in Figure II.33, the transition of energy from one coil to the next, such as from coil A to coil B, prompts a physical rotation of the rotor to achieve alignment with the new field orientation. [71, 80, 50, 37]

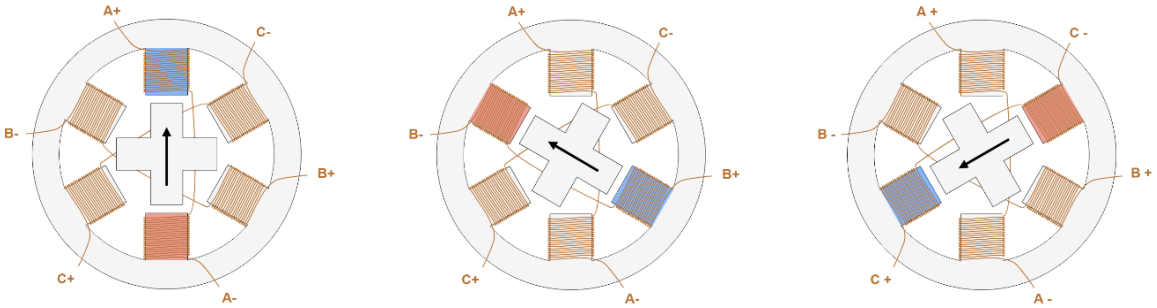
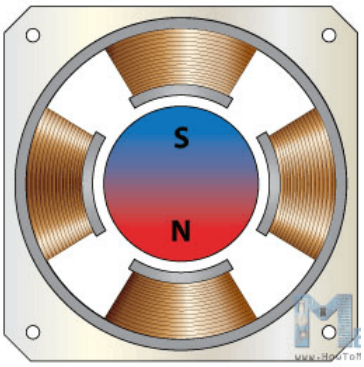


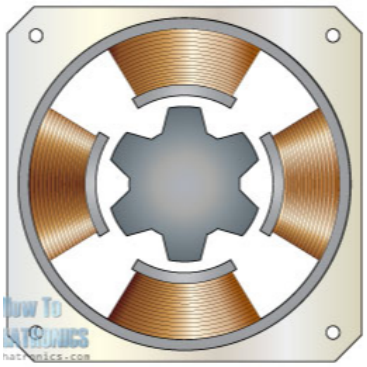
Figure II.33: Stepper motor working principle

– **Construction types:** Stepper motors are commonly classified into three main construction types: permanent magnet, variable reluctance, and hybrid. These types differ mainly in the way the rotor is built and in the way magnetic alignment is produced during operation, which directly affects torque and step resolution.

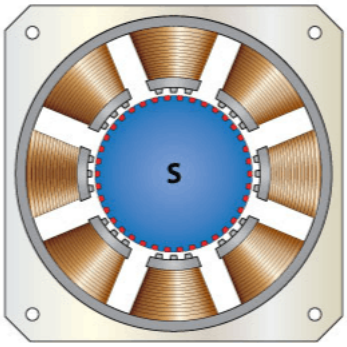
  * Permanent magnet stepper motors use a rotor that contains a permanent magnet, as shown in Figure II.34 (a), which gives the motor a stronger magnetic interaction with the stator field. This type can provide better low-speed torque and a clear holding effect when the windings are energized. However, its step resolution and overall performance are generally lower, so it is more suitable for simpler motion systems than for precision CNC axes. Its main value lies in its straightforward construction and its ability to provide a reliable basic stepping motion.
  * Variable reluctance stepper motors use a soft-iron toothed rotor without a permanent magnet, as shown in Figure II.34 (b). The rotor moves because it tends to align itself with the energized stator poles, so the magnetic circuit is repeatedly attracted toward the position of minimum reluctance. This construction is relatively simple and compact, but it generally provides lower torque and less favorable holding performance. For this reason, variable reluctance motors are less common in CNC systems where stable low-speed torque and repeatable positioning are required.
  * Hybrid stepper motors combine the features of permanent magnet and variable reluctance designs, as shown in Figure II.34 (c). The rotor has two sections, which are opposite in polarity, and their teeth are offset, as shown in Figure II.34 (d). It is toothed and magnetized, which improves the interaction between the rotor and stator fields and allows smaller step angles, higher torque, and better positioning accuracy. Because of this combination, hybrid motors offer the best balance between resolution, torque, and control quality, which explains why they are the most widely used type in CNC applications. Their construction is more complex than that of the other two types, but this added complexity is justified by the better motion performance they provide. [50, 37]



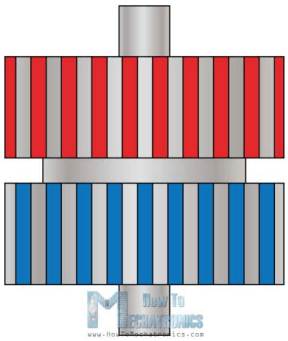
(a) Permanent magnet stepper motor



(b) Reluctance stepper motor



(c) Hybrid stepper motor



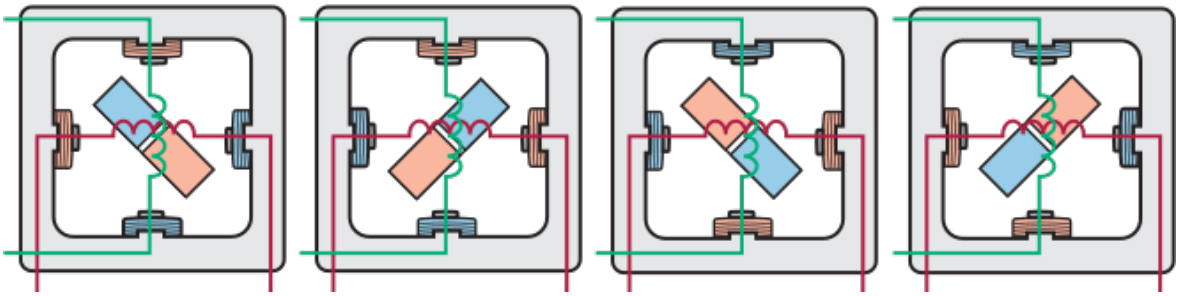
(d) Hybrid stepper motor's rotor

Hybrid stepper motor construction

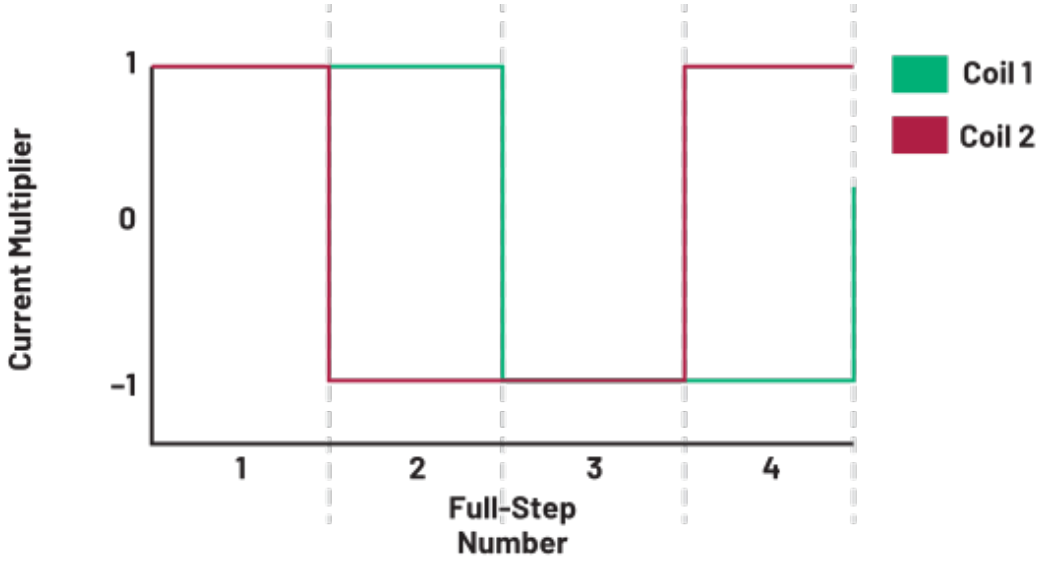
Figure II.34: Stepper motor different constructions

– **Driving modes:** The operational performance of a stepper motor is significantly influenced by its drive mode, which dictates how the stator phases are energized to produce rotor motion. These modes represent increasing levels of control complexity and offer different trade-offs between torque, positioning resolution, and motion smoothness.

  * In full-step operation, the motor advances through its fundamental step angle by energizing the stator phases in a defined sequence, as shown in Figure II.35 (b), typically using two-phase excitation where both windings are powered simultaneously, as shown in Figure II.35 (a). This configuration provides the highest available static torque, as the magnetic field is fully established. However, the resulting motion occurs in discrete increments, which can lead to noticeable mechanical excitation. At certain speeds, this may induce resonance phenomena, generating vibration and acoustic noise within the CNC structure.



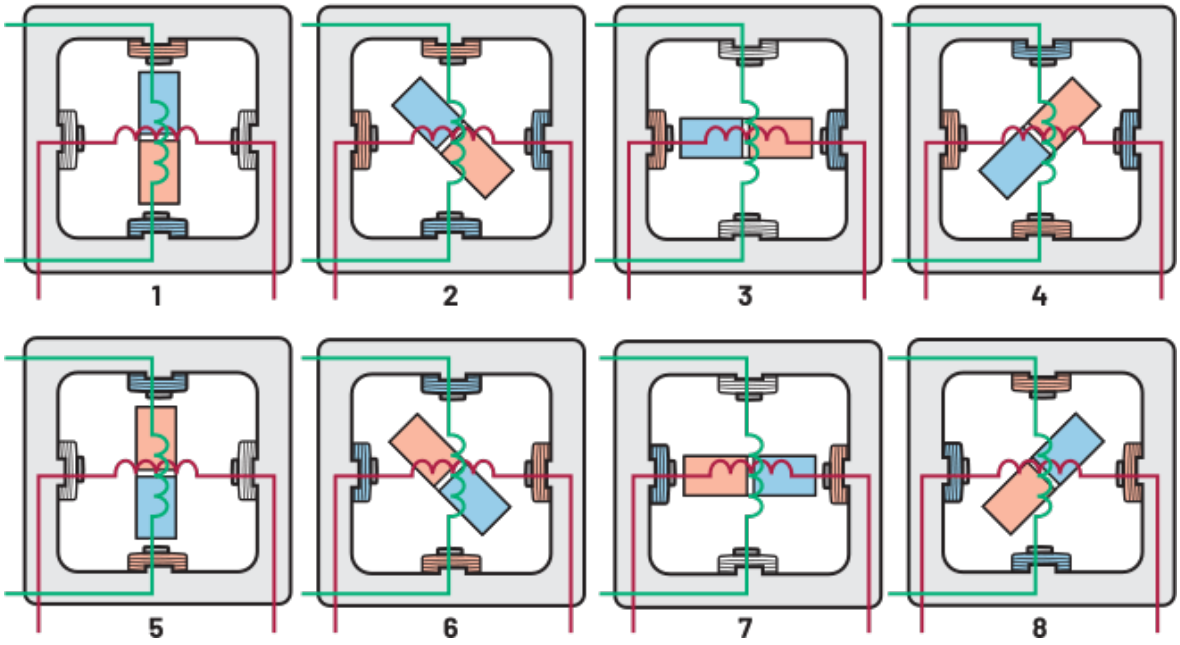
(a) Two-phase full-step excitation sequence



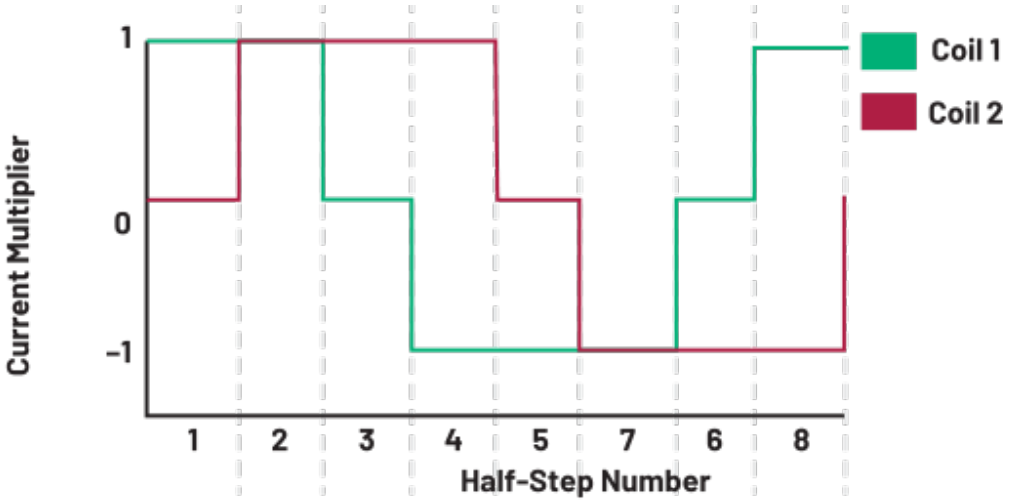
(b) Phase current distribution in full-step mode

Figure II.35: Two-phase stepper motor in full-step mode

* Half-step operation improves positioning resolution by alternating between single-phase and dual-phase excitation, as shown in Figure II.36 (b). This creates intermediate equilibrium positions, effectively reducing the step angle by half, as shown in Figure II.36 (a). As a result, motion becomes smoother and more refined compared to full-step operation. However, this method introduces torque variation, since the torque produced during single-phase excitation is lower than that of dual-phase excitation. Despite this limitation, half-stepping provides a practical compromise between simplicity, improved resolution, and reduced vibration.



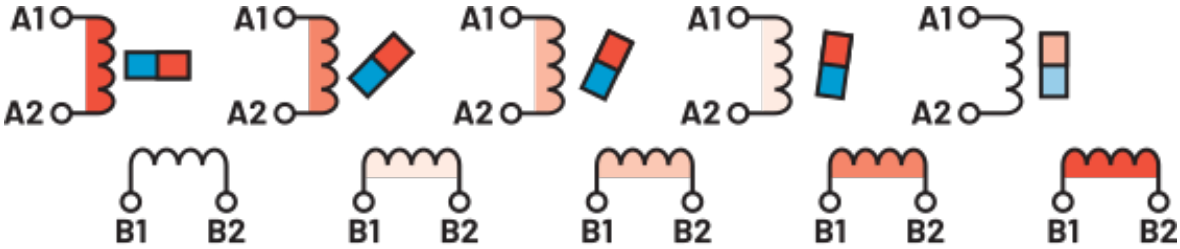
(a) Two-phase half-step excitation sequence



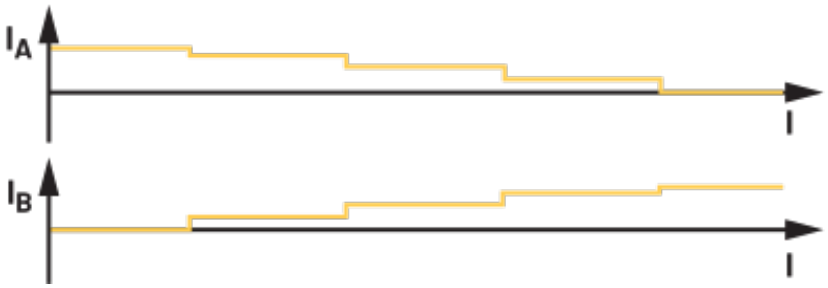
(b) Phase current distribution in half-step mode

Figure II.36: Two-phase stepper motor in half-step mode

* Microstepping represents the most advanced drive mode, where the controller does not simply turn the phases on or off but instead modulates the current in each winding using sine and cosine waves to generate a smoothly rotating magnetic field, as shown in Figure II.37 (b). This allows the rotor to move in very small increments between full steps, significantly improving motion smoothness and reducing mechanical vibration, as shown in Figure II.37 (a). Such behavior is particularly important in CNC applications where trajectory continuity and surface finish are critical. Nevertheless, the incremental torque available between microsteps is lower than the full-step torque, which can affect the ability of the motor to resist disturbances under load. [37, 15]



(a) Two-phase microstepping excitation sequence



(b) Phase current distribution in microstepping mode

Figure II.37: Two-phase stepper motor in microstepping mode

– **Difference in number of wires:** Stepper motors are also available with different lead-wire configurations, typically 4, 6, or 8 wires, as shown in Figure II.38. A 4-wire motor is usually a bipolar motor and is simple to connect, but it must be driven by a bipolar driver. A 6-wire motor can be used as either unipolar or bipolar, depending on how its center taps are connected, which gives more wiring flexibility. An 8-wire motor offers even more connection options because the windings can be configured in series or parallel, allowing the designer to favor either higher torque at lower speed or better high-speed performance. In practice, the choice of wire count affects both the driver compatibility and the electrical behavior of the motor, so it must be matched carefully to the controller and the required operating range. [93]

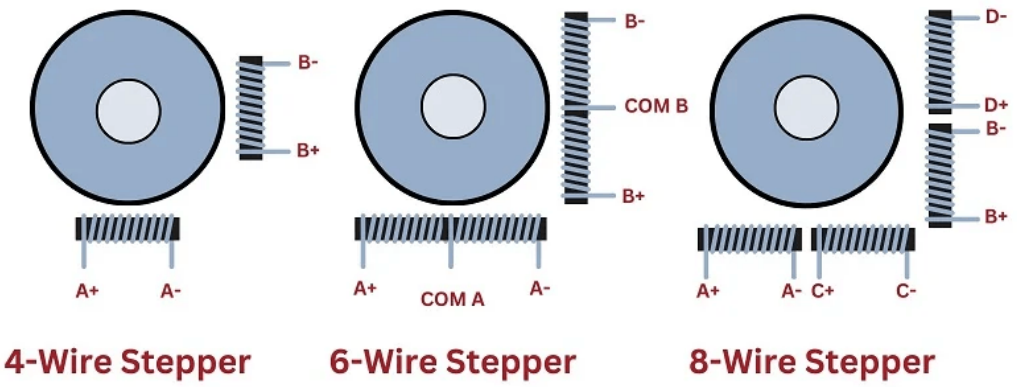


Figure II.38: Wiring schemes for 4-wire, 6-wire, and 8-wire steppers

- **Advantages:** Simple control structure, relatively low cost, good low-speed torque, strong holding torque at standstill, and easy integration into open-loop CNC systems. [71]

- **Drawbacks:** Torque decreases as speed increases, resonance may appear in some operating ranges, and open-loop operation can lose position if the load is too high or the acceleration is excessive. [71]

- **Suitability:** Suitable for small and medium CNC machines, prototype systems, and applications where moderate speed, moderate load, and simple control architecture are more important than very high dynamic performance.

- **Servo motors**

  - **Description** Servomotors are special electromechanical devices that produce precise degrees of rotation. A servo motor is a DC or AC or brushless DC motor combined with a position sensing device. Servomotors are also called control motors as they are involved in controlling a mechanical system. [92]

    The servomotors are used in a closed-loop servo system, as shown in Figure II.39. A reference input is sent to the servo amplifier, which controls the speed of the servomotor. A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback. This feedback is sent to the error detector, which compares the actual operation with that of the reference input. If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action. In many servo systems, both velocity and position are monitored. Servomotors provide accurate speed, torque, and have ability of direction control.[92]

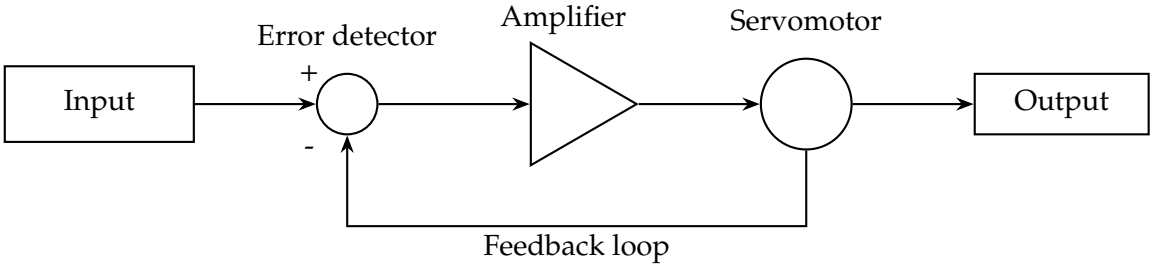


Figure II.39: Closed-loop servo control system

DC operated servomotors are usually respond to error signal abruptly and accelerate the load quickly. A DC servo motor is actually an assembly of four separate components:

* **DC motor:** A DC servo motor system is composed of several essential

components that work together to achieve controlled motion. The DC motor itself provides the mechanical rotation by converting electrical energy into torque. Its speed and direction are determined by the applied voltage and current, making it the primary actuator of the system.

* **gear assembly:** The gear assembly is used to adapt the motor output to the required application. By reducing speed and increasing torque, it allows the system to handle higher loads while improving positioning resolution.
* **position-sensing device:** A position-sensing device, such as an encoder or potentiometer, continuously measures the actual position or speed of the motor shaft. This measurement is essential for feedback, as it enables the system to compare the real motion with the commanded one and detect any deviation.
* **control circuit:** The control circuit processes the error between the desired and measured position and generates the appropriate control signal for the motor. It regulates the current supplied to the motor in order to minimize this error, ensuring accurate positioning and stable operation under varying load conditions. [92]

In the AC servo motors, the magnetic force is generated by a permanent magnet and current which further produce the torque. It has no brushes so there is little noise/vibration. This motor provides high precision control with the help of high resolution encoder. The stator is composed of a core and a winding. The rotor part comprises of shaft, rotor core and a permanent magnet. Digital encoder can be of optical or magnetic type. It gives digital signals, which are in proportion of rotation of the shaft. [92]

– **Advantages:** Provides a high torque to inertia ratio and high speeds, work well for velocity control. Available in all sizes, quiet in operation, smoother rotation at lower speeds. [92]

– **Drawbacks:** More expensive than stepper motors, require tuning of control loop parameters, not suitable for hazardous environments or in vacuum, excessive current can result in partial demagnetization of dc type servo motor. [92]

– **Suitability:** Suitable for industrial CNC axes, high-performance machines, and applications where accurate tracking, fast response, and stable motion under load are required.

The choice of drive motor in CNC systems spans a range of technologies that differ in complexity, performance, and control strategy. While stepper motors and servo motors represent the most commonly used solutions for open-loop and closed-loop control, respectively, other alternatives are also relevant in advanced applications. Direct drive systems eliminate mechanical transmission elements, providing very high precision and dynamic response at the cost of increased complexity and inte-

gration requirements. In addition, closed-loop stepper systems, often referred to as hybrid servos, combine the simplicity of stepper motor architecture with encoder feedback to improve torque utilization and eliminate missed steps. Overall, these alternatives highlight the gradual progression in CNC drive technology from simple open-loop control toward fully integrated high-performance motion systems.

II.3.2.3 Limit switches

Limit switches are used in CNC machines to define the travel boundaries of each axis, to establish homing positions, and to protect the machine from overtravel. They provide the control system with a clear signal when a moving component reaches a predefined position, which makes them an essential part of both safety and referencing. In practice, they are divided into contact-based mechanical limit switches and non-contact proximity limit switches:

II.3.2.3.1 Mechanical limit switches

- **Description:** Mechanical limit switches operate based on direct physical contact between the moving part of the CNC axis and the actuator of the switch. When the actuator is engaged, an internal spring mechanism causes the electrical contacts to change state, generating a discrete signal that indicates the end of travel or a reference position. Then, as the object is pushed off the actuator, the internal return spring forces the actuator and contacts to their original normal position. The switch is then prepared for the next detection cycle. [90, 81]

  These switches are commonly available in two electrical configurations: normally open (NO) and normally closed (NC), as shown in Figure II.40 (a) and Figure II.40 (b) respectively. In a normally open configuration, the circuit remains open until the switch is actuated, at which point it closes and allows current to flow. In contrast, a normally closed configuration maintains a closed circuit in its default state and opens when actuated. In CNC applications, NC configurations are often preferred for safety-related functions, since any wire break or fault will be interpreted as an open circuit, immediately signaling an error condition.[90]



(a) Normally open limit switch (b) Normally closed Limit switch

Figure II.40: Limit switch configurations

At the core of most mechanical limit switches is the microswitch, which is a compact electromechanical device that provides a rapid and well-defined change of state. Internally, a typical microswitch contains two switching contacts that share a common terminal: one normally open (NO) and one normally closed (NC). This configuration is known as Single Pole Double Throw (SPDT), where both contacts are mechanically linked and change state simultaneously when the actuator is triggered, as shown in Figure II.41. This arrangement ensures a reliable and instantaneous switching action, which is essential for accurate position detection. It should be noted, however, that not all microswitches follow this configuration; some are designed as Single Pole Single Throw (SPST) switches, providing only a single switching function with two terminals. [81]

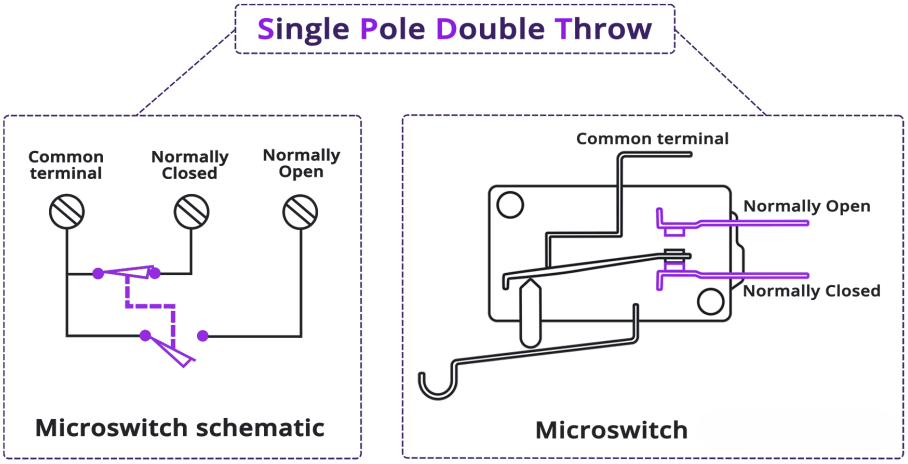
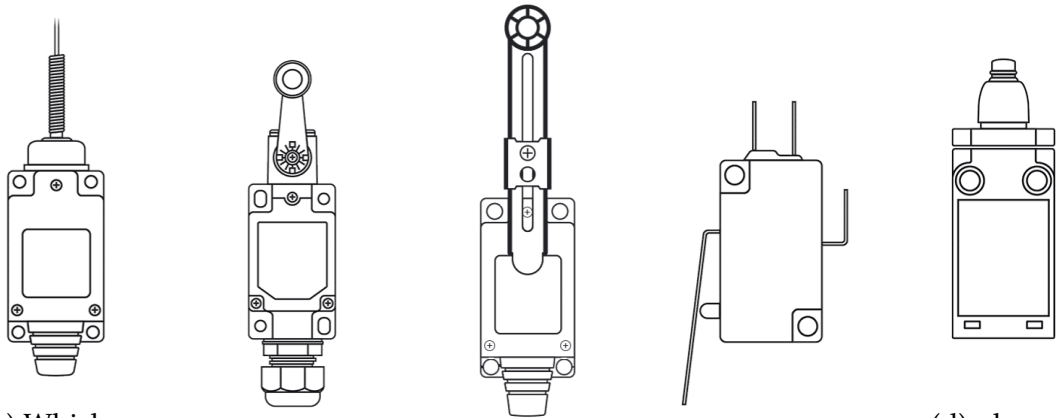


Figure II.41: Microswitch

Mechanical limit switches are available in several actuator forms, which mainly differ in how the external motion is transferred to the internal switch mechanism:

- **Whisker type:** This type uses a flexible wire actuator that can be deflected with minimal force, as shown in Figure II.42 (a). It is highly sensitive and can detect contact from multiple directions, but it is also more fragile and less suitable for harsh environments compared to other types.
- **Roller type:** Roller switches incorporate a small rotating wheel at the end of the actuator, as shown in Figure II.42 (b). This reduces friction and wear during repeated contact. It is suitable for scenarios where the object slides past and pushes the switch. It is commonly used on conveyor belts.
- **Lever type:** Lever switches use a hinged arm to transmit motion to the internal mechanism, as shown in Figure II.42 (c). They provide a larger actuation range and can accommodate misalignment between the moving part and the switch, which makes them more flexible in installation.

– **Plunger type:** Plunger switches are activated by a direct axial, vertical or straight-line force applied to a spring-loaded pin, as shown in Figure II.42 (d). They offer a simple and compact design with a precise actuation point, but they require accurate alignment and direct contact with the moving element.[90, 81]



(a) Whisker switch (b) Roller switch (c) lever switch (d) plunger switch

Figure II.42: Mechanical limit switch Types

- **Advantages:** Mechanical limit switches offer several advantages, including simple construction, low cost, ease of integration, and clear switching behavior. [66]

- **Drawbacks:** they also present drawbacks such as mechanical wear, contact bounce, and reduced long-term repeatability due to repeated physical contact. [66]

- **Suitability:** low-cost CNC machines, basic homing operations, and end-of-travel protection, where simplicity and reliability are more critical than high precision and long-term durability.

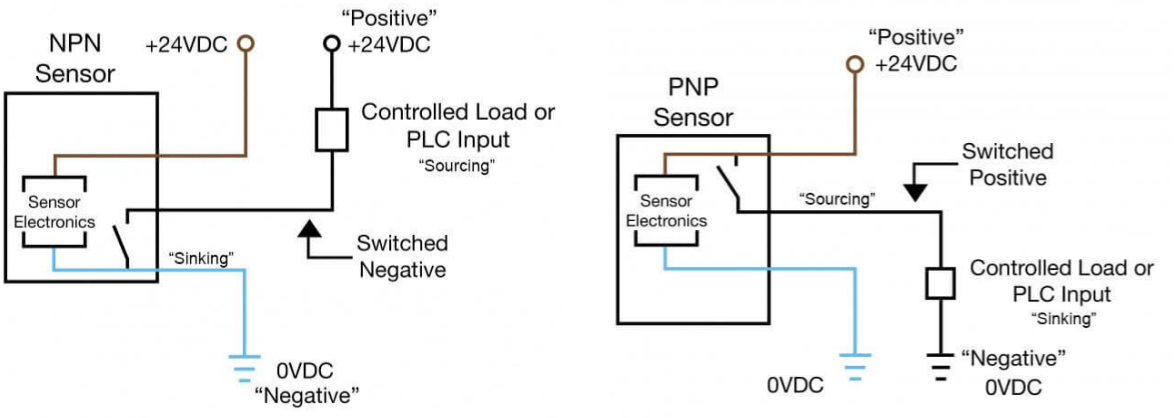
II.3.2.3.2 Proximity limit switches

- **Description:**Proximity limit switches operate without direct physical contact, detecting the presence of a target when it enters a defined sensing field. Unlike mechanical switches, the working principle relies on the interaction between the sensor and the target through physical phenomena such as electromagnetic fields, electric fields, light, or sound waves. When the target is detected, the sensor changes its output state, generating a signal that indicates the position of the axis. This non-contact operation eliminates mechanical wear and enables consistent performance over a large number of cycles. [69]

Similar to mechanical switches, proximity sensors are commonly available

in normally open (NO) and normally closed (NC) configurations. In the NO configuration, the output signal is activated only when the target is detected, whereas in the NC configuration, the sensor provides a continuous signal that is interrupted upon detection. In CNC systems, NC configurations are often preferred for safety-critical applications, since any loss of signal due to wiring faults or power issues can be interpreted as a fault condition, ensuring safer operation.

At the core of a proximity sensor is an internal electronic switching circuit that processes the detection signal and controls the output stage. Unlike mechanical contacts, the output stage of proximity sensors is implemented electronically, most commonly using transistor-based switching. These outputs are typically classified as either NPN (sinking) or PNP (sourcing). In an NPN configuration, the sensor provides a path to ground when activated (active LOW output), meaning the load is connected to the positive supply and current flows through the sensor to ground. This is referred to as a **sinking** output, as shown in Figure II.43 (a). In contrast, a PNP configuration supplies current to the load when activated (active HIGH output), with the load connected to ground, which is known as a **sourcing** output, as shown in Figure II.43 (b). The choice between NPN and PNP depends on the input requirements of the CNC controller or interface hardware. Additionally, when the sensor is not activated, the output may be considered in a high-impedance or **floating** state, particularly in transistor-based designs, meaning it neither actively sources nor sinks current. This behavior must be properly managed through pull-up or pull-down configurations to ensure reliable signal interpretation within the control system. [46]



(a) NPN proximity switch (b) PNP proximity switch

Figure II.43: NPN & PNP proxity switches

Proximity limit switches are available in several types, which mainly differ in the physical principle used for detection:

– **Inductive type:** Inductive sensors generate an electromagnetic field at the sensing face and detect the presence of metallic objects through the

disturbance of this field, as shown in Figure II.44. They are highly robust, immune to dust, oil, and coolant, and are therefore the most commonly used type in CNC machines. Their limitation is that they can only detect conductive (metallic) targets.

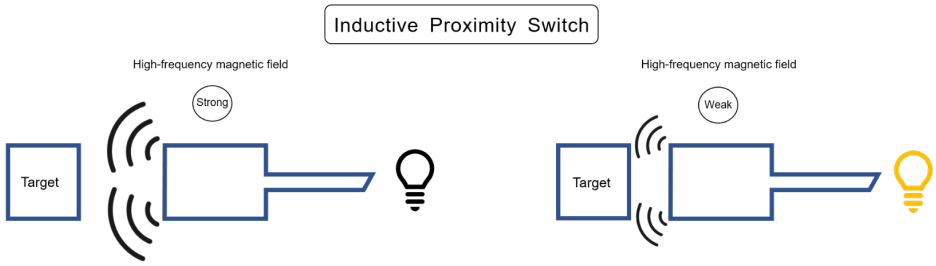


Figure II.44: Inductive proximity switch

– **Capacitive type:** Capacitive sensors are similar to inductive ones but use a capacitor to generate an electric field. When an object enters its electric field, the capacitance value changes, triggering the sensor, as shown in Figure II.45. Therefore, they can detect both metallic and non-metallic materials, including plastics and liquids. However, this property gives them an obvious edge in safety applications, where a foreign object could be any material. It makes them more sensitive to environmental conditions such as humidity and contamination, which can affect their stability.

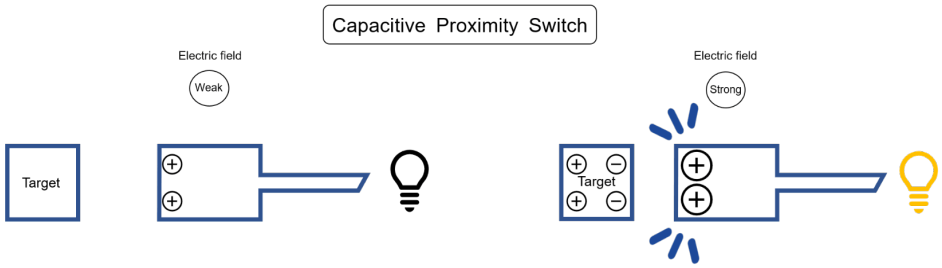


Figure II.45: Capacitive proximity switch

– **Photoelectric type:** Photoelectric proximity switches use light to detect objects. Their working principle is based on the use of the sensor to the reflector to reflect light back to the sensor so that the sensor can detect the presence of the object based on the reflected light, as shown in Figure II.46. They offer long sensing distances and fast response times. Their main drawback is their sensitivity to dust, misalignment, and surface reflectivity, which can reduce reliability in harsh machining environments.

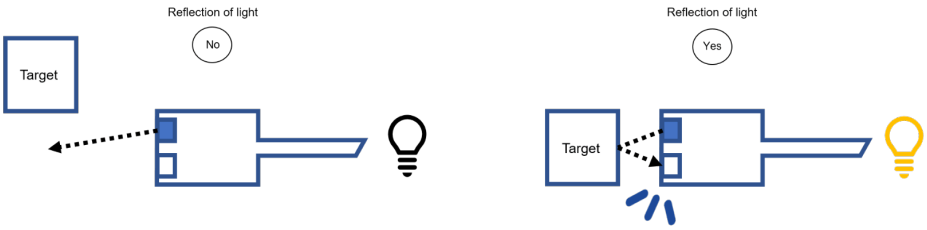


Figure II.46: Photoelectric proximity switch

– **Ultrasonic type:** Ultrasonic sensors emit high-frequency sound waves and measure the reflected signal to detect the presence of an object, as shown in Figure II.47. They are capable of detecting a wide range of materials, including transparent and irregular surfaces. However, they are generally slower than optical sensors and can be affected by environmental conditions such as temperature and air turbulence. [69, 10]

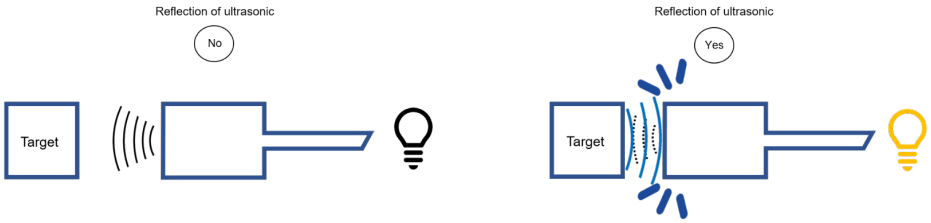


Figure II.47: Ultrasonic proximity switch

- **Advantages:** non-contact operation, high durability, absence of mechanical wear, and improved repeatability. They also provide faster response and more stable long-term performance compared to mechanical switches. [66]

- **Drawbacks:** higher cost, sensitivity to installation conditions, and, depending on the type, limitations related to target material or environmental influence. [66]

- **Suitability:** industrial CNC machines, high-cycle operations, and applications where reliability, precision, and minimal maintenance are required.

In summary, limit switches constitute a fundamental element in CNC systems, ensuring safe operation through reliable position detection and travel limitation. The selection between these technologies depends on the required level of precision,

environmental conditions, and system reliability, making it a critical aspect of overall machine design.

II.3.2.4 CNC spindle system

The spindle system is a fundamental component of a CNC machine, responsible for generating the rotational motion required for material removal. It acts as the interface between the machine and the cutting tool, transmitting mechanical power while maintaining precise control over speed, stability, and positioning, which is important as it directly affects machining accuracy, surface finish, and productivity. [58, 77]

The mechanical design of a CNC spindle is centered around a high-precision rotating shaft supported by a specialized bearing arrangement housed within a rigid structure, as shown in Figure II.48. The shaft interfaces with the cutting tool through standardized holders, such as ER collets or taper-based systems, ensuring concentric alignment and secure clamping under high centrifugal forces. Bearings represent one of the most critical components of the spindle, as they determine its stiffness, rotational accuracy, and maximum allowable speed. High-speed spindles typically employ angular contact ball bearings or hybrid ceramic bearings to achieve low friction, high rigidity, and reduced thermal expansion.[57]

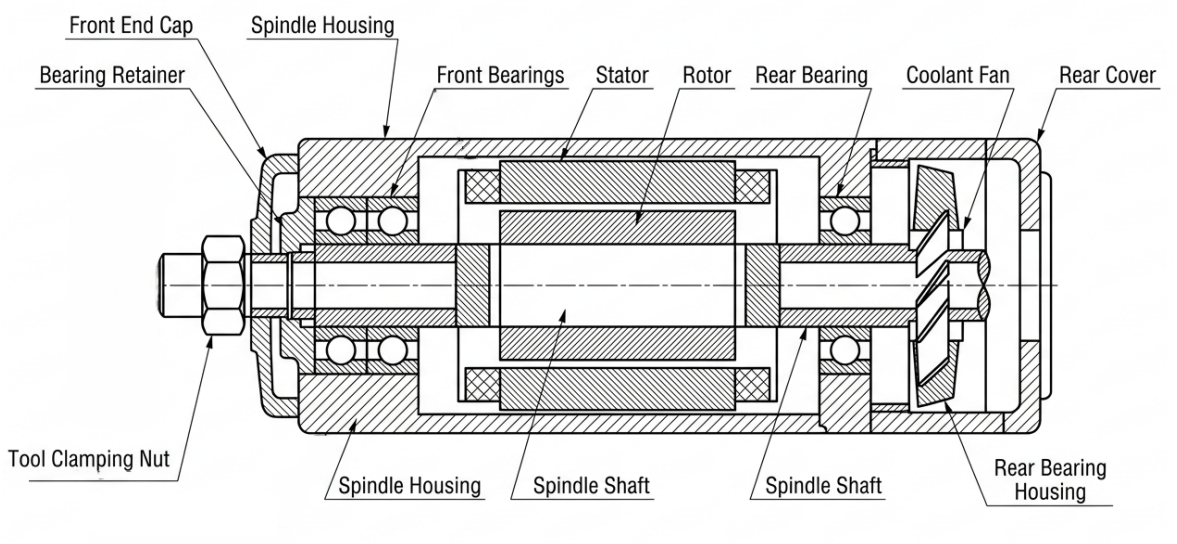


Figure II.48: Spindle construction

The spindle housing provides structural support and maintains precise alignment between the shaft and the bearings, while also serving as a medium for active heat dissipation. Particular attention is given to minimizing runout (the deviation of the tool axis from its ideal rotational path measured at the tool tip), as even microscopic errors can significantly affect machining precision and surface finish. The overall construction must therefore ensure a balance between structural rigidity and dynamic performance, allowing the spindle to withstand substantial cutting forces while maintaining the high rotational speeds necessary for modern automation. [58]

Modern CNC spindles are predominantly driven by brushless motors, typically in the form of permanent magnet synchronous motors (PMSM), due to their high efficiency, reliability, and ability to operate over a wide speed range. In this configuration, the stator (fixed to the spindle housing) contains three-phase windings supplied with controlled alternating currents, while the rotor is directly attached to the spindle shaft and carries permanent magnets, as shown in Figure II.49. This arrangement allows the motor to generate torque without mechanical contact, eliminating the need for brushes and significantly reducing wear and maintenance requirements.[86]

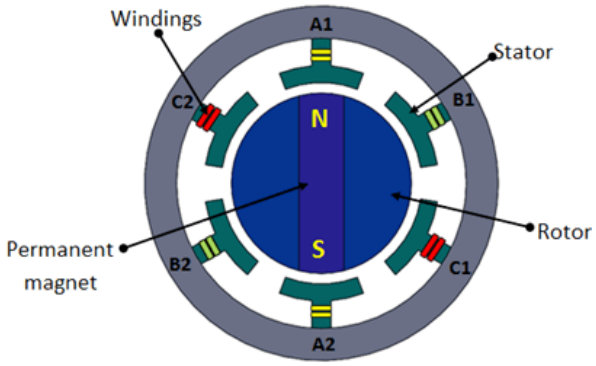


Figure II.49: Brushless DC motor

The operating principle is based on the generation of a rotating magnetic field within the stator. By supplying the stator windings with three-phase currents that are phase-shifted in time, a magnetic field is created that rotates at a speed determined by the input frequency. The permanent magnets on the rotor tend to align with this rotating field, causing the rotor (and therefore the spindle shaft) to follow it synchronously. As a result, the rotational speed of the spindle can be precisely controlled by adjusting the frequency of the supply, while the torque is regulated through the current amplitude.[77]

To achieve this level of control, the spindle motor is driven by a variable frequency drive (VFD), which converts the fixed-frequency electrical supply into a controlled three-phase signal with adjustable frequency and voltage. In advanced configurations, the system operates in closed-loop control using feedback from sensors such as encoders, allowing precise regulation of speed and torque under varying load conditions. This is particularly important in CNC machining, where cutting forces can change dynamically during operation.[77, 91]

Thermal management is a critical aspect of spindle design, as heat is generated by both the motor and the bearings during operation. Excessive temperature rise can lead to thermal expansion, reduced bearing life, and loss of machining accuracy. To mitigate these effects, CNC spindles are equipped with cooling systems, which are typically classified as air-cooled or liquid-cooled. [118]

Air-cooled spindles rely on forced airflow to dissipate heat and are generally simpler and more cost-effective, making them suitable for light-duty applications. In contrast, liquid-cooled spindles use a circulating coolant, usually water or a water-based mixture, to achieve more efficient and stable heat removal. This approach is preferred in high-speed and high-precision applications, where thermal stability is

essential. [118]

In summary, the spindle system represents a key element in CNC machine design, integrating mechanical, electrical, and thermal aspects to deliver controlled rotational motion. Its design directly influences machining performance, accuracy, and reliability. By carefully selecting and optimizing the spindle components, motor type, and cooling strategy, it is possible to achieve a balanced system that meets the demands of modern manufacturing applications.

II.3.3 Software ecosystem and control architectures

Modern CNC systems rely not only on mechanical and electrical components, but also on a structured software ecosystem that governs the entire machining process. From the initial design of a part to its physical realization, a sequence of interconnected software tools is used to define geometry, generate machining instructions, and control machine motion. This digital workflow ensures that complex parts can be produced with high precision and repeatability, while also enabling flexibility in design and manufacturing.

The software chain in CNC machining typically follows a well-defined progression, starting with computer-aided design (CAD), followed by computer-aided manufacturing (CAM), post-processing, and finally execution through control software. Each stage plays a specific role and must be properly configured to ensure compatibility with the others, as errors or mismatches at any level can propagate throughout the system and affect the final result. Consequently, understanding the interaction between these software components is essential for achieving reliable and efficient machining operations.

II.3.3.1 CAD stage (Design)

The computer-aided design (CAD) stage represents the starting point of the CNC workflow, where the geometry of the part is created and defined. In this phase, the user develops a digital model using parametric or direct modeling techniques, specifying dimensions, constraints, and geometric relationships that describe the final component. The accuracy and completeness of this model are critical, as they directly influence all subsequent stages of the process. [2, 64]

In addition to defining geometry, CAD models often include information about tolerances, surface quality, and assembly relationships, which may guide later machining decisions. Modern CAD software provides advanced tools for visualization, simulation, and modification, allowing designers to validate their concepts before manufacturing. For CNC applications, the model must be clean, well-constrained, and free of geometric inconsistencies, as these issues can lead to errors during toolpath generation in the CAM stage. [2, 64]

Furthermore, the CAD stage establishes the reference coordinate system and orientation of the part, which are later used in the machining setup. A well-defined coordinate framework simplifies the transition to CAM and ensures consistency

between the virtual model and the physical machine. As a result, careful preparation at the CAD level contributes significantly to reducing errors and improving the overall efficiency of the CNC workflow.

Commonly used CAD software in CNC applications includes SolidWorks and Autodesk Fusion 360. These tools provide advanced modeling capabilities, parametric design features, and integrated simulation environments, enabling the creation of precise and reliable digital models suitable for subsequent manufacturing stages.

II.3.3.2 CAM stage (Toolpath generation)

The CAM (Computer-Aided Manufacturing) stage is responsible for converting the geometric model created in the CAD environment into a set of executable machining instructions. In this phase, the digital model is imported into CAM software (such as MasterCam or an integrated CAM add-on on SolidWorks or Fusion 360), where the user defines how the part will be manufactured. This involves selecting machining operations, defining toolpaths, and specifying the tools required to remove material. The generated toolpaths represent the trajectory that the cutting tool will follow relative to the workpiece, taking into account the machine kinematics and the chosen setup. The accuracy of this stage is critical, as any error in toolpath generation directly affects the final part quality. [63, 64]

A fundamental aspect of the CAM process is the selection of appropriate machining strategies, which determine how material is removed from the workpiece. Common strategies include roughing, finishing, drilling, and contouring. Roughing operations aim to remove large amounts of material efficiently, often using aggressive cutting parameters and toolpaths designed to minimize machining time. Finishing operations, on the other hand, focus on achieving the desired surface quality and dimensional accuracy, typically using finer stepovers and lower cutting forces. Drilling operations are used for hole-making processes, while contouring strategies follow the geometry of the part to produce precise edges and profiles. The choice of strategy depends on the material, geometry, and required surface finish, making it a critical step in optimizing machining performance. [63, 64]

In addition to strategy selection, the CAM stage requires careful definition of machining parameters, including cutting speed, feed rate, depth of cut, and tool selection. These parameters directly influence cutting forces, tool wear, and overall machining efficiency. For instance, higher feed rates can reduce machining time but may increase tool load and vibration, while lower speeds improve surface finish at the expense of productivity. Tool selection is equally important, as different tools are optimized for specific operations and materials. Proper parameter tuning ensures a balance between productivity, tool life, and machining quality, and is often refined through experience or simulation within the CAM environment. [63, 64]

II.3.3.3 Post-Processing and G-code generation

The post-processing stage serves as the interface between the CAM environment and the physical CNC machine, converting the generated toolpaths into a machine-

readable program, typically in the form of G-code. While CAM software defines the geometry of the tool motion, it does not inherently account for the specific characteristics of a given CNC machine. This task is handled by the post-processor, which translates generic toolpath data into a structured set of instructions that conform to the syntax, coordinate system, and control logic of the target machine controller. As a result, the post-processor plays a critical role in ensuring that the intended tool motion is accurately executed by the machine. [114, 79]

A key function of the post-processor is to adapt the toolpaths to the specific configuration and kinematics of the CNC system. This includes defining axis movements, coordinate transformations, tool orientation, and machine limits. The importance of this adaptation becomes particularly evident in multi-axis machining, such as 5-axis systems, where the relationship between rotational and linear axes must be precisely managed. In such cases, the post-processor is responsible for converting tool orientation data into synchronized axis commands, ensuring smooth and collision-free motion. Without a properly configured post-processor, even correctly generated toolpaths may result in incorrect or unsafe machine behavior.[114, 79]

For standard industrial machines, post-processors are often provided by the machine manufacturer or the CAM software vendor. However, in the case of custom or DIY CNC machines, obtaining a suitable post-processor requires additional effort. In such configurations, the user may need to adapt an existing post-processor or develop a custom one that matches the specific kinematics, axis configuration, and controller requirements of the machine. This process typically involves modifying parameters such as axis naming conventions, motion limits, tool change routines, and output syntax to ensure compatibility with the control software. Many CAM platforms provide editable post-processor frameworks, allowing users to tailor the generated G-code to their machine. Consequently, the ability to understand and customize post-processors becomes an essential skill in the development and operation of non-standard CNC systems.[114, 79]

II.3.3.4 Control software and execution

The control software represents the final stage of the digital workflow, where the generated G-code is interpreted and translated into real-time motion commands. Common CNC control platforms include MAch3/4, LinuxCNC, and UGS, which provide the interface between the user and the machine. These programs read the G-code line by line, interpret motion commands, and generate the corresponding signals required to drive the machine axes, spindle, and auxiliary systems. In doing so, the control software ensures that the intended toolpath is accurately executed according to the programmed instructions.

In addition to interpreting G-code, the control system must communicate effectively with the underlying hardware, including motion controllers, motor drivers, and input/output devices. This interaction is governed by strict real-time constraints, as motion commands must be executed with precise timing to maintain synchronization between axes and avoid trajectory deviations. Any delay or inconsistency in signal generation can lead to positioning errors, surface defects, or unstable machine behavior.

In summary, the software ecosystem of a CNC system plays a fundamental role in bridging the gap between digital design and physical manufacturing. Each stage, from CAD modeling to control execution, contributes to the accuracy, efficiency, and reliability of the machining process. A well-integrated and properly configured software chain ensures that the intended geometry is faithfully reproduced while minimizing errors and optimizing performance. Consequently, mastering this digital workflow is essential for achieving high-quality results in modern CNC machining, particularly in advanced and custom-built systems.

Conclusion

This chapter has presented a comprehensive overview of the fundamental components and subsystems that constitute a modern CNC machine, covering mechanical transmission systems, rotational drives, electrical hardware, sensing elements, spindle systems, and the associated software ecosystem. Each element was analyzed not only in terms of its structure and working principle, but also with respect to its performance, limitations, and suitability within different machining contexts.

Particular emphasis was placed on the interaction between these subsystems, highlighting that the overall performance of a CNC machine does not depend on individual components alone, but rather on the coherence and integration of the entire system. From the selection of transmission mechanisms and drive motors to the configuration of controllers and software tools, each design decision directly influences accuracy, dynamic behavior, and operational reliability. This interconnected perspective is especially important in advanced configurations, such as multi-axis CNC machines, where mechanical complexity and control requirements are significantly increased.

Furthermore, the chapter underscored the importance of the digital workflow, demonstrating how CAD, CAM, post-processing, and control software collectively enable the translation of a virtual design into a physical part. The proper alignment of these software stages with the machine hardware ensures that machining instructions are executed accurately and efficiently, reducing errors and enhancing productivity.

In the context of custom and experimental CNC systems, such as the one developed in this work, the understanding and careful selection of these components become even more critical. The absence of standardized configurations requires a deeper level of analysis and adaptation, particularly in areas such as post-processing, control architecture, and system integration. Consequently, this chapter provides the theoretical and technical foundation necessary for the design, implementation, and optimization of the CNC machine presented in the following sections.

CHAPTER III

Prototype assembly and system setup

Introduction

This chapter presents the practical realization of the CNC prototype, describing the precise steps followed to transform the theoretical design into a functional machine. After defining the mechanical architecture, the transmission systems, the electrical components, and the software environment in the previous chapters, the focus now shifts to the physical assembly and integration of the system. This stage is critical, the actual performance and precision of the machine depend not only on the selected components but equally on the quality of their mechanical alignment, electrical wiring, and system configuration.

The chapter is organized into three main stages. The first stage details the mechanical assembly, including the construction of the base frame, the installation of the standard linear axes, and the critical mounting of the bi-rotary head. The second stage covers the electrical and electronic integration, emphasizing power distribution, safe circuitry, stepper drive installation, sensor wiring, and the overall cabinet layout. The final stage addresses the software and control implementation, focusing on the controller configuration, system calibration, and initial testing. Together, these steps ensure that the prototype operates as a highly unified mechatronic system, providing the necessary foundation for evaluating its behavior in practice.

III.1 Mechanical system integration

The mechanical part of the prototype concerns the structural elements that support the machine and define its motion architecture. It includes the frame, the axis supports, and the different mechanical subassemblies that guide the movement of the linear and rotary axes. In a CNC machine, the mechanical structure must provide sufficient rigidity, geometric stability, and load-carrying capacity so that the motion system can operate under controlled conditions without excessive deformation or misalignment.

For this prototype, the mechanical assembly is therefore not limited to putting components together, but rather to building a structure capable of supporting the

intended kinematic design. The frame must sustain the arrangement of the linear axes and the rotary axes while preserving the relative positions required for accurate motion. In this sense, the mechanical assembly establishes the physical foundation of the machine.

III.1.1 Frame construction and mounting

The first step in physically realizing the CNC prototype was constructing the primary frame. The objective was to build a rigid rectangular box-structure capable of supporting a heavy, moving overhead gantry while providing a stable, stationary base for the workpiece.

This material was selected because it is highly modular, cost-effective, and allows for rapid assembly and adjustment during the prototyping phase. As evaluated in the theoretical chapters, industrial machines typically rely on high-mass materials like epoxy-granite or cast iron to dampen high-frequency vibrations. While an aluminum frame lacks this heavy mass, it provides a highly practical and sufficiently rigid alternative for verifying the kinematics of a prototype.

The frame was constructed entirely from 20-series extruded aluminum profiles, selected for their modularity, cost-effectiveness, and ease of adjustment. The overall footprint of the machine is approximately [Insert X] mm x [Insert Y] mm x [Insert Static Z] mm. This relatively large geometric volume was intentionally established to maximize the internal work envelope. Because the 5-axis architecture utilizes a bi-rotary head where all angular articulation occurs at the tool, the cutting head requires significant spatial clearance to pivot around the stationary workpiece without causing mechanical collisions with the frame.

To optimize the frame's strength-to-weight ratio, two different profile geometries were utilized:

- The Base and Pillars: The lower perimeter and the vertical support pillars were built using standard 40x40 mm profiles, cut to lengths of 850 mm and 650 mm, respectively.
- The Gantry Supports: To carry the dynamic, moving weight of the overhead gantry without sagging, the upper horizontal rails required a higher moment of inertia. For these, heavy-duty 40x80 mm C-Beam profiles were used, cut to lengths of 890 mm and 810 mm, as shown in Figure III.1.

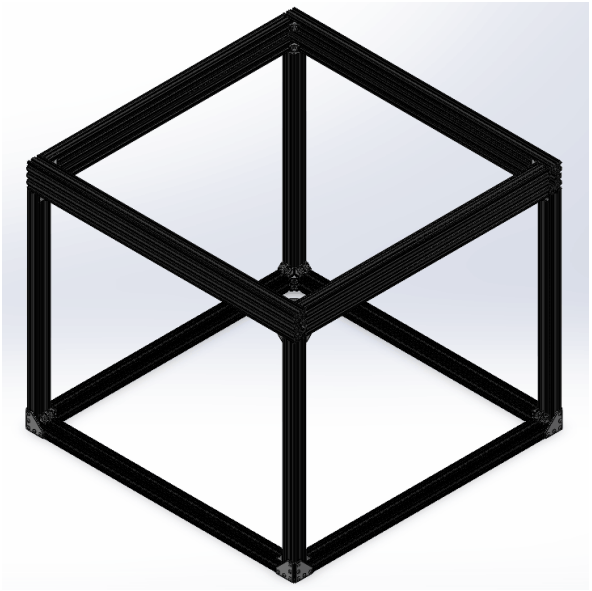
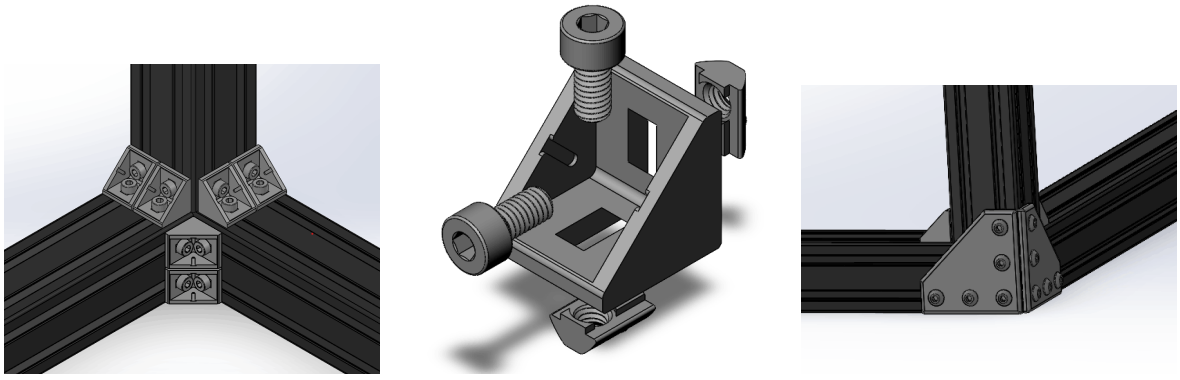


Figure III.1: Prototype's frame

A frame is only as rigid as its joints. To prevent the aluminum profiles from shifting or twisting under machining loads, the structure was assembled using a high-tension fastening system. Internally, the intersections are secured using 90-degree die-cast corner brackets, as shown in Figure III.2 (a), clamped tightly with M5 drop-in T-nuts and 8 mm low-profile bolts, as shown in Figure III.2 (b). To further reinforce the structure against torsional twisting, external aluminum joining plates were bolted across all critical corners, as shown in Figure III.2 (c), locking the entire geometry into a rigid, unified base.



(a) Frame corner fixture (b) Corner bracket parts (c) Corner join plate

Figure III.2: Frame corner assembly

While extruded aluminum provides an ideal platform for rapid prototyping, its inherent lack of mass makes the frame highly susceptible to resonance and high-frequency vibrations during physical machining operations. In the custom and DIY CNC community, it is a common practice to mitigate this issue by filling the hollow cavities of aluminum profiles with sand or an epoxy-resin mixture to increase the structural mass and improve vibration damping artificially. Due to resource

constraints during this project, the profiles were left hollow. However, with the extensive use of external reinforcement plates and heavy C-Beam gantry supports, the current framework possesses sufficient mechanical stiffness to safely and accurately validate the kinematic behavior of the 5-axis system.

III.1.2 Linear axis integration (X-Y-Z)

The linear axis assembly represents the dynamic core of the CNC prototype. Although the X, Y, and Z axes share the same fundamental mechanical architecture based on C-beam extrusions, linear guide rails, and ball screw transmissions, their specific configurations vary significantly depending on their hierarchical position within the kinematic chain. The careful integration of these components dictates the overall geometric accuracy, repeatability, and load-bearing capacity of the machine.

III.1.2.1 X-Axis integration

The X-axis forms the main support of the moving gantry, since it carries the combined mass of the Y-axis, the Z-axis, and the cutting head. For this reason, it was designed as a rigid dual-drive system with two identical and parallel mechanical assemblies mounted on opposite sides of the main machine frame, as shown in Figure III.3. Each side is built around an 890 mm long C-beam aluminum extrusion. This profile was selected because it offers high bending resistance and provides large flat surfaces that are well-suited for mounting the guiding elements and the transmission system.

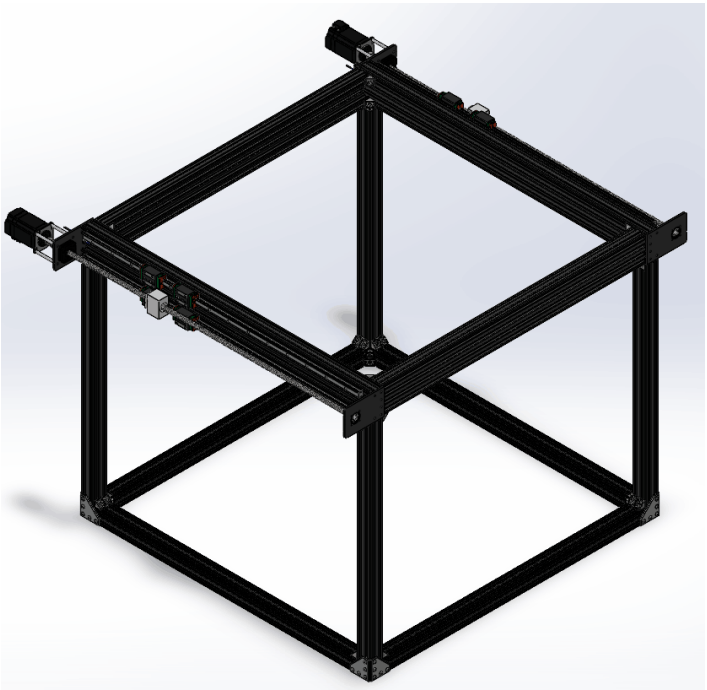


Figure III.3: X-axis assembly mounted on the main structural frame

To ensure smooth and stable movement of the gantry along the X direction, a precision linear guiding system was installed along the extreme outer edges of each

C-beam, as shown in Figure III.4, leaving the hollow central channel free. The rails were fixed using M4 bolts and drop-in T-nuts along their length, in order to ensure proper alignment and load distribution. Each rail carries two linear bearing blocks, resulting in a total of four bearing carriages for the axis. This arrangement improves stability and allows the system to support the weight of the gantry while minimizing unwanted rotational motion and deflection during operation.

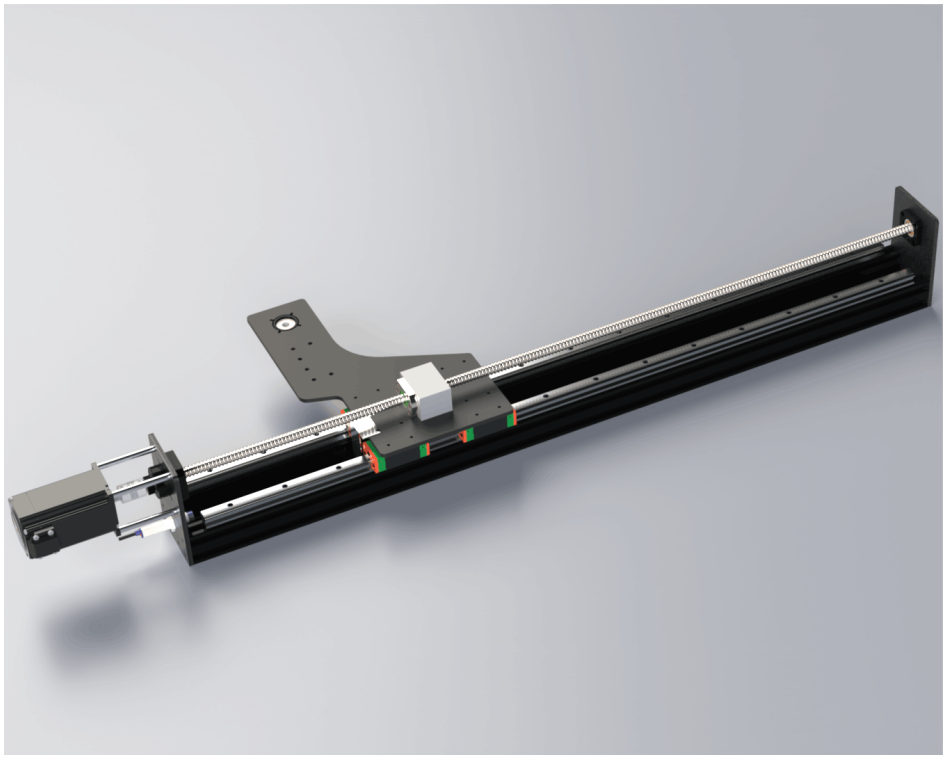
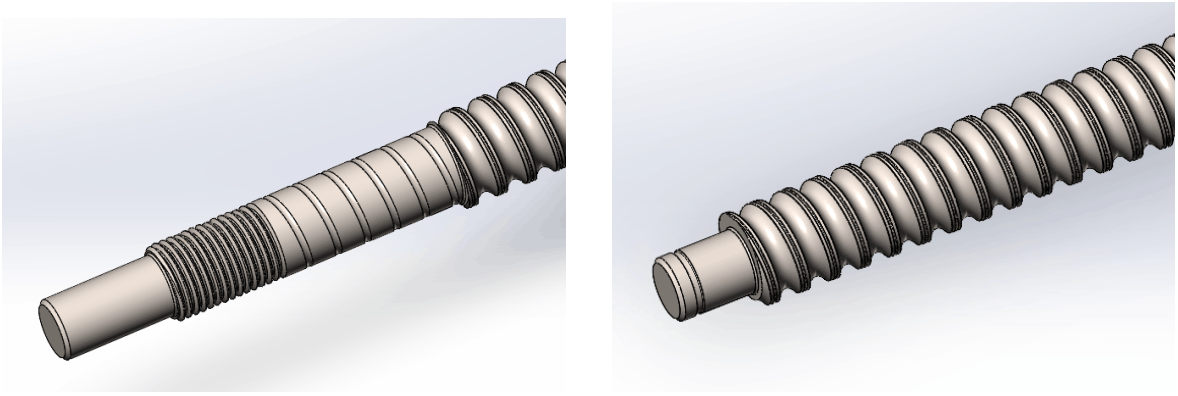


Figure III.4: X-axis assembly

The transmission system of the X-axis is based on a 1204 ball screw with an effective assembled length of 940 mm. However, an integration issue appeared during the fabrication stage because the closest commercially available ball screw had a standard length of 1000 mm. Unlike conventional threaded rods, ball screws cannot simply be cut to the desired length, as their ends are machined with precise geometries intended to fit the support bearings and locking elements, as shown in Figure III.5. To solve this issue, the simpler end of the screw (as shown in Figure III.5 (b)), which only contained a retaining circlip groove, was re-machined on a lathe until the required length was obtained. This modification preserved the functional geometry of the support interfaces while adapting the component to the dimensions of the machine.



(a) Threaded ball screw end (b) Groove (simple) ball scew end

Figure III.5: Ball screw ends

The ball screw is supported at both ends using FK10 and FF10 support bearing blocks mounted on a custom 5 mm iron plate. This plate was manufactured using a fiber laser cutting machine to ensure dimensional accuracy and proper alignment between the support bearings and the transmission axis. The assembly plate is fixed directly to the extremity of the C-beam profile and also serves as the mounting interface for the stepper motor. The motor is attached using extended mounting screws and spacers, while torque transmission between the motor shaft and the ball screw is ensured through a flexible shaft coupling designed to compensate for minor alignment errors.

In conventional C-beam axis assemblies, the ball screw is generally positioned inside the hollow section of the extrusion profile. However, in this prototype, the dimensions of the ball nut housing exceeded the available internal space of the beam, preventing internal integration of the transmission system. As an alternative solution, the ball screw was mounted externally above the profile. To accommodate this configuration, the central iron interface plate connecting the X-axis to the Y-axis assembly was positioned between the ball nut housing and the linear bearing blocks, this created a highly effective sandwich configuration. Although this arrangement complicated the assembly process due to the accessibility of the fastening screws from both sides of the plate, it provided sufficient mechanical clearance that solidly connects the X-axis transmission to the Y-axis, resulting in a functional and rigid assembly.

The main connection plate linking the X-axis to the Y-axis was also manufactured using fiber laser cutting. This method was chosen to guarantee precise dimensions and perfectly aligned mounting holes. This iron plate acts as the central structural bridge for the moving gantry. It solidly connects the linear bearing blocks, the external ball nut housing, and the ends of the Y-axis together into one unified moving unit.

The final component installed on the X-axis is an inductive proximity sensor, which acts as the homing switch. This sensor is securely mounted just underneath the stepper motor. To trigger it, a small metal target piece is attached directly to the moving iron carriage plate. As the carriage approaches the end of its travel, the stationary sensor detects this metal target and signals the controller to stop. This

setup allows the machine to reliably find its "home" zero position and safely prevents the carriage from physically crashing into the ends of the frame.

III.1.2.2 Y-Axis integration

The Y-axis assembly is mounted directly onto the moving X-axis structure, as shown in Figure III.6, and is responsible for carrying the Z-axis and spindle assembly along the transverse direction of the machine. Similar to the X-axis, the Y-axis was constructed around a C-beam aluminum extrusion profile in order to provide sufficient rigidity while maintaining a compact and modular structure. The selected profile has a length of 950 mm and supports both the guiding and transmission systems required for precise linear motion.

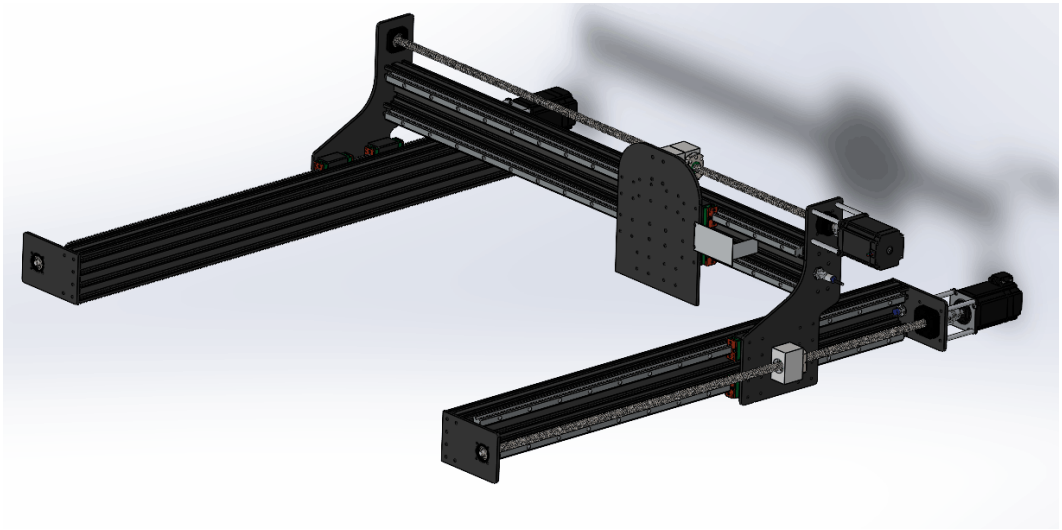


Figure III.6: X and Y axes assembly

The guiding mechanism of the Y-axis consists of two linear guide rails mounted along the outer edges of the C-beam profile, as shown in Figure III.7. Each rail carries two linear bearing blocks, resulting in a total of four bearing carriages distributed across the axis, just like the X axis.

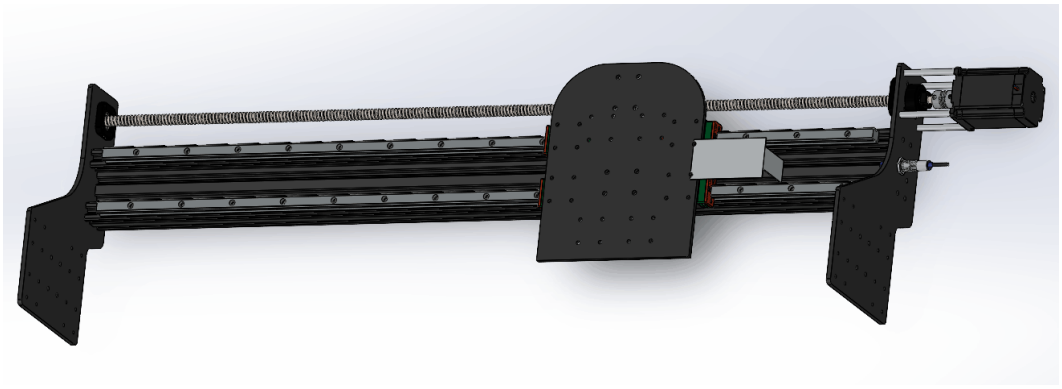


Figure III.7: Y-axis assembly

The transmission system is based on a 1204 ball screw that was machined to a final length of 970 mm in order to fit the dimensions of the assembly. Unlike the X-axis configuration, the positioning of the ball screw was modified to accommodate the structural arrangement of the machine. Instead of being aligned directly above the central interface plate, the transmission assembly was positioned further back using spacers to offset the motor and support system. This design choice was necessary because the Z-axis assembly is mounted on the front face of the Y-axis carriage, leaving insufficient clearance for the ball screw and nut assembly there.

The ball screw is supported at both ends using FK10 and FF10 support bearing blocks mounted onto the 5 mm iron side plates connecting the X-axis and Y-axis assemblies. These plates also serve as the mounting interface for the stepper motor, which is fixed using long mounting screws and spacers to achieve the required alignment with the screw axis. Torque transmission between the motor shaft and the ball screw is achieved through a flexible shaft coupling designed to compensate for minor alignment errors. In addition, an inductive homing limit sensor was installed beneath the motor assembly to provide a reliable reference position during machine initialization and homing procedures. To trigger this sensor, a small metal target piece is attached directly to the outer edge of the moving Y-to-Z connection plate. As the Y-axis carriage travels toward the extremity of the frame, the stationary sensor detects this metal target and immediately signals the controller to stop. This setup ensures the machine can accurately find its zero position while acting as a physical safety limit to prevent the axis from over-traveling and crashing into the frame.

The complete Y-axis assembly is securely fixed to the moving X-axis gantry structure, forming the intermediate stage between the horizontal motion system and the vertical Z-axis assembly. This configuration provides sufficient rigidity and positional stability while maintaining adequate clearance for the integration of the remaining machine components.

III.1.2.3 Z-Axis integration

The Z-axis assembly shapes the vertical motion of the machine and supports the complete spindle and rotary head assembly. Similar to the previous axes, the structure of the Z-axis is based on a C-beam aluminum extrusion profile with an approximate length of 600 mm. Linear guidance is ensured through two guide rails mounted along both sides of the profile, each equipped with two linear bearing blocks, providing stable vertical motion and adequate support for the machining head during operation, as shown in Figure III.8.

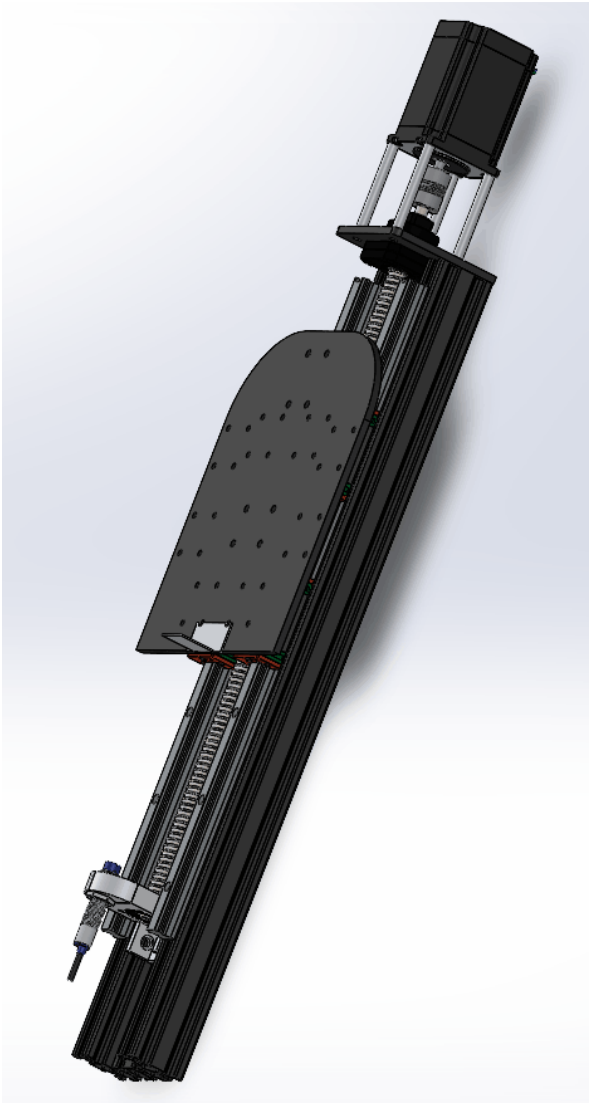


Figure III.8: Z-axis assembly

The transmission system of the Z-axis is based on a 1204 ball screw with a length of 500 mm. Unlike the ball screws used in the X-axis and Y-axis assemblies, this screw did not require machining and was installed using its original dimensions. Although slightly shorter than the intended design, it remained suitable for the required travel range of the vertical axis. Unlike the X-axis and Y-axis assemblies, the transmission system of the Z-axis could not be mounted externally above the C-beam profile due to the geometric constraints created by the Y-axis structure. As a result, the transmission system was integrated directly inside the hollow section of the C-beam.

To make this internal integration possible, a custom ball nut housing was designed and manufactured using 3D printing technology, as shown in Figure III.9. The dimensions of this housing were specifically adapted to fit inside the internal cavity of the extrusion while securely holding the ball nut in position. This approach allowed the transmission system to remain compact and aligned with the center of the axis without interfering with the surrounding structural elements.

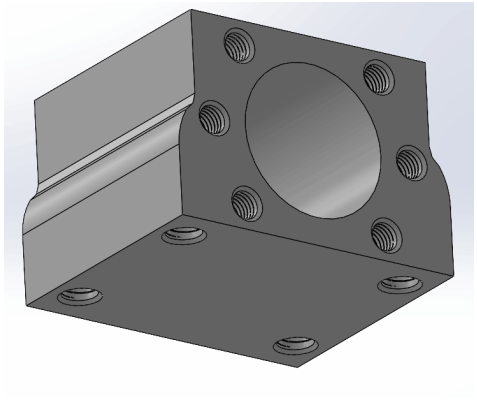


Figure III.9: Z-axis ball nut housing model

The actuation of the Z-axis is provided by a stepper motor mounted at the upper end of the C-beam on an iron mounting plate. The motor is fixed using long mounting bolts and spacers in order to achieve proper alignment with the screw axis, while transmission is ensured through a flexible shaft coupling connected directly to the ball screw. The screw itself is supported at the motor side through an end-support bearing block mounted on the same iron plate. On the opposite side, instead of using another external iron support plate, a second custom-designed 3D printed support holder was manufactured to fit inside the C-beam profile and support the lower end of the screw, as shown in Figure III.10. This solution was adopted because the lower region of the axis needed to remain extended and unobstructed to allow the future integration of the A-axis and C-axis rotary assemblies.

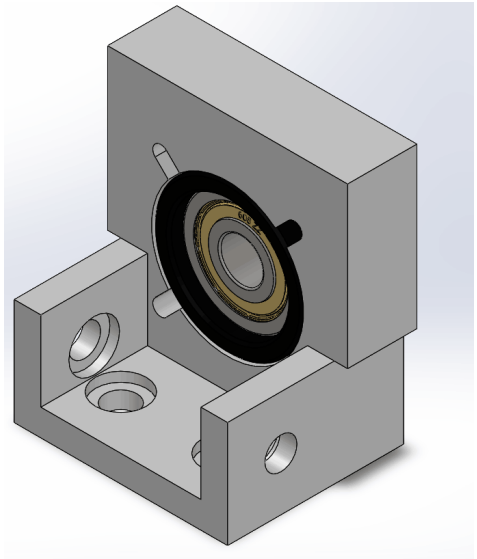


Figure III.10: Z-axis ball screw end bearing support

The homing system of the Z-axis also differs from the previous axes. In this configuration, the inductive proximity sensor was mounted near the lower end of the assembly, directly above the internal 3D printed support holder. A metallic trigger plate was fixed onto the Y-to-Z interface plate so that the sensor could detect the reference position during the homing sequence. This arrangement was selected

because the homing position of the Z-axis corresponds to the fully raised position of the spindle assembly, making the upper travel limit the safest and most appropriate machine reference for vertical motion initialization.

The most critical component of the Z-axis assembly is the custom iron Y-to-Z connection plate. This plate acts as the structural intersection between the horizontal movement of the Y-axis and the vertical movement of the Z-axis, as shown in Figure III.11. Because it must interface with the guiding and driving mechanisms of both axes simultaneously, it serves as the central anchor of the moving gantry.

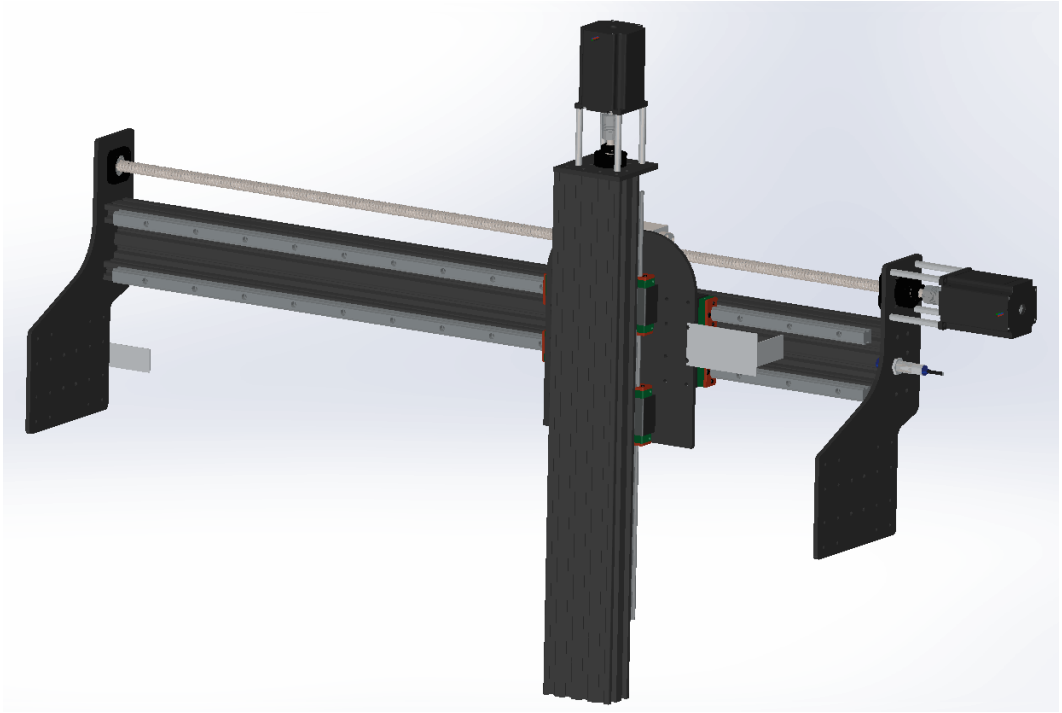


Figure III.11: Y and Z axes assembly

On its back face, the plate is securely bolted to the four linear bearing blocks of the Y-axis, as well as the external Y-axis ball nut housing. This setup means that when the Y-axis motor turns, it drives the entire iron plate horizontally across the gantry bridge.

On its front face, the plate connects to the Z-axis. It is bolted directly to the Z-axis linear bearing blocks and the Z-axis ball nut housing. This creates a very specific dynamic between the two axes. The Y-axis physically moves the plate left and right, but the Z-axis simply uses the plate as a stationary vertical anchor. When the Z-axis motor turns, the Z-axis extrusion and the heavy cutting head glide up and down along the front of the plate. The plate itself never moves vertically; it just holds the Z-axis perfectly perpendicular, so it can slide smoothly against it without twisting.

III.1.3 Rotary axes integration (A-C)

The bi-rotary head is the defining mechanical feature of this 5-axis architecture. It is responsible for all angular tool orientations, completely separating the rotational

movements from the stationary worktable. To simplify the development process, the baseline geometry of the head was adapted from an existing open-source design. However, extensive CAD modifications were required to customize the geometry, ensuring it properly integrated with the specific dimensions, C-beam extrusions, and hardware of this prototype.

The head, as shown in Figure III.12, is divided into two distinct rotational joints: the C-axis, which pans vertically around the Z-axis, and the A-axis, which tilts horizontally around the X-axis. To keep the moving mass as low as possible while achieving these complex shapes, the majority of the head's framework was manufactured using a 3D printer.

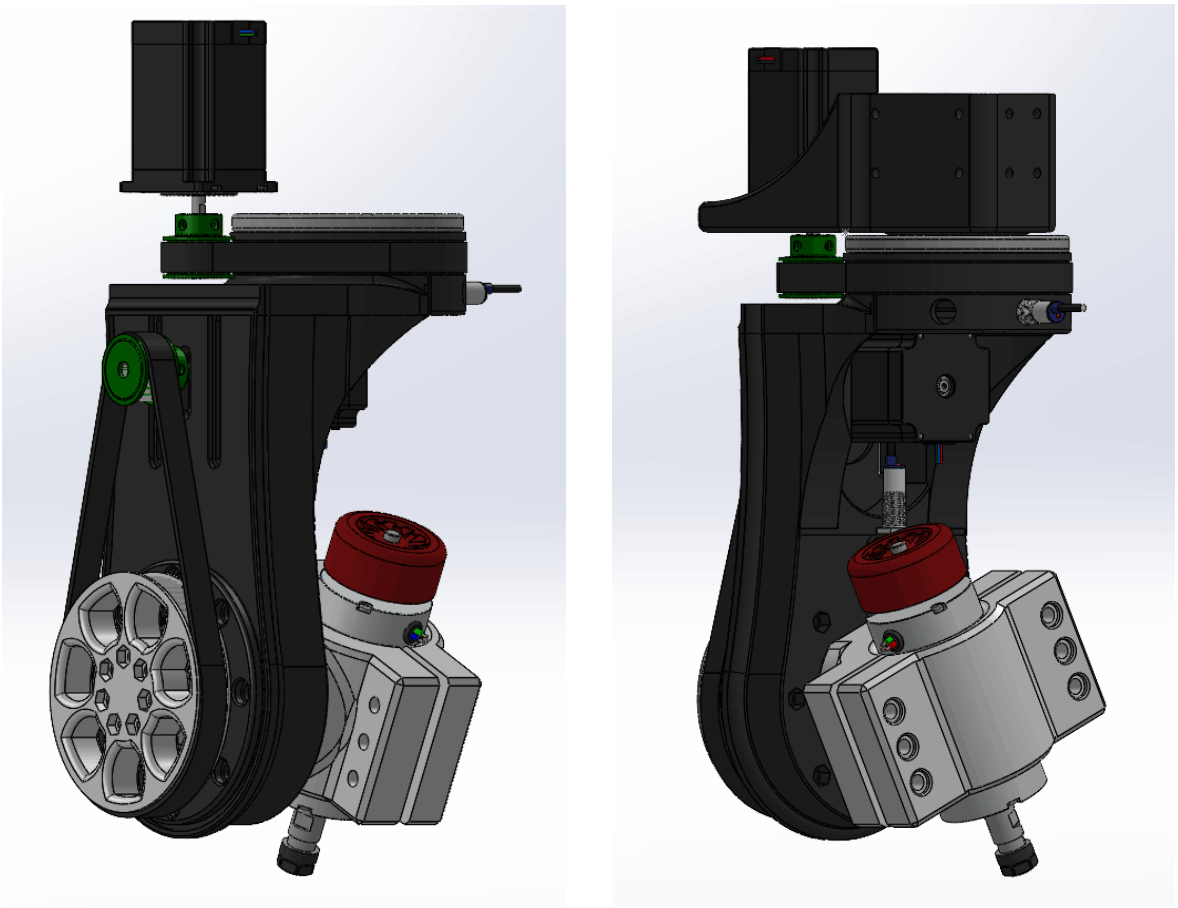


Figure III.12: A and C axes assembly

The entire assembly attaches to the bottom of the Z-axis C-beam. A custom 3D-printed adapter slots inside the aluminum extrusion, serving as the stationary base, as shown in Figure III.13. The rotation between this base and the moving head relies on standard deep groove ball bearings. While these bearings successfully handle the rotational loads, they inherently exhibit a slight amount of vertical play (axial clearance). Upgrading to angular contact bearings or thrust bearings would eliminate this vertical deflection, but for the scope of this prototype, the standard bearings were sufficient to validate the 5-axis kinematics.

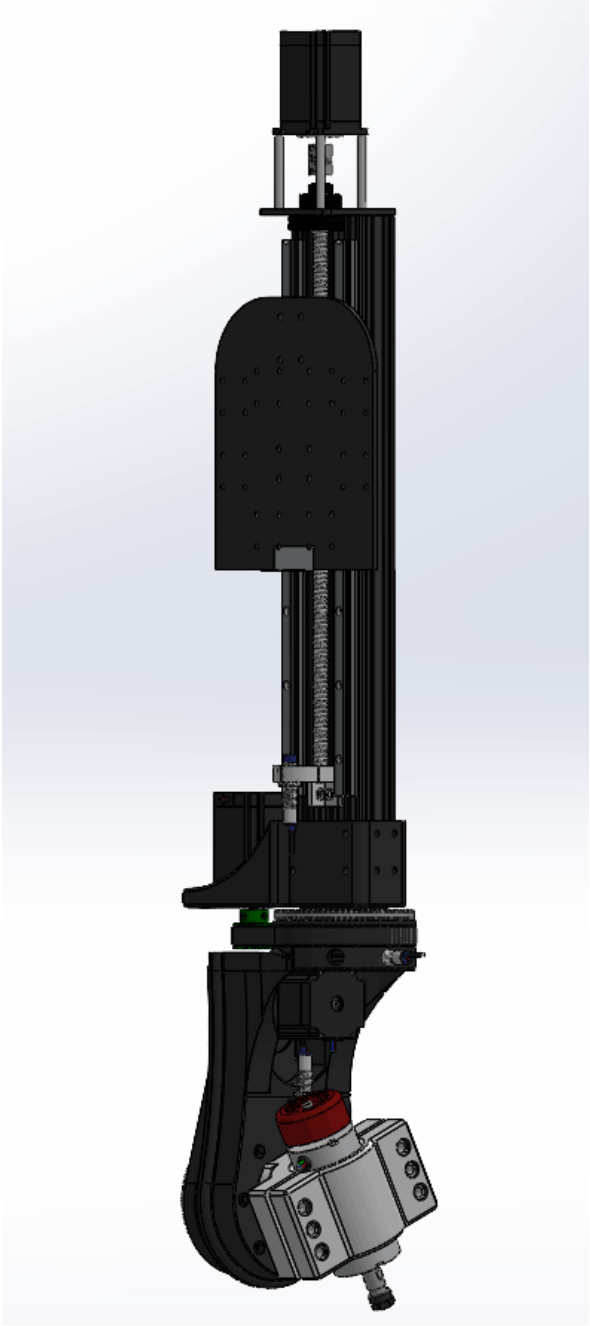


Figure III.13: A, B, and Z axes assembly

Both the C-axis and the A-axis utilize identical transmission architectures to move. They are driven by stepper motors connected to HTD5M (5 mm pitch & 15 mm width) timing belts, which are highly suited for accurate positioning. For both axes, the motor is fitted with a small 20-tooth driving pulley that turns a large 72-tooth driven pulley. This specific combination creates a 3.6:1 mechanical gear reduction. This reduction sacrifices top rotational speed to significantly multiply the motor's holding torque and increase the angular resolution, both of which are essential for keeping the tool rigid during machining.

For the C-axis, the 72-tooth pulley is integrated directly into the 3D-printed rotating body. For the A-axis, the motor sits directly on the rotating arm and drives

the large pulley connected to the pivoting spindle holder, as shown in Figure III.14. This holder is customized to securely clamp a 500W Brushless DC (BLDC) spindle, chosen because it provides an excellent balance of high cutting speeds and low physical weight, preventing the 3D-printed arms from bending under heavy loads.

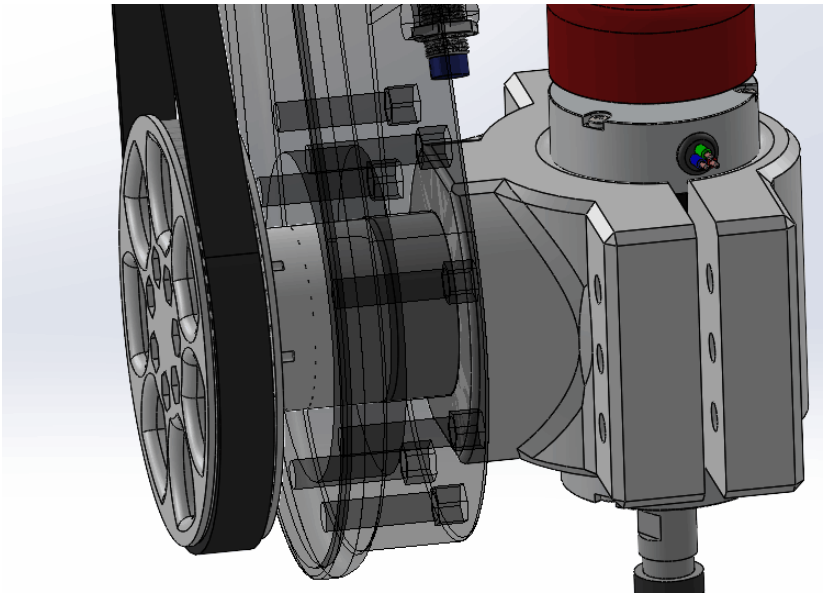


Figure III.14: Spindle holder connection to A-axis pulley

Finally, just like the linear axes, the rotary axes must be able to find their true zero positions before machining begins. This is achieved using inductive proximity sensors integrated into the 3D-printed housing. These sensors allow the controller to accurately establish the true zero angle for both the pan (C) and tilt (A) orientations during the homing sequence.

III.1.4 Working table construction and mounting

With the dynamic kinematic axes fully assembled, the final mechanical component is the stationary worktable. Because this CNC prototype utilizes a head-head configuration, the worktable does not move during operation. Its sole purpose is to provide a rigid, flat, and reliable surface for clamping the workpiece.

The primary surface of the table is constructed from a 12 mm thick wood plate. To ensure perfect squareness and precise dimensions, the board was cut using a laser CNC machine to a final size of 600 mm by 600 mm. During the laser cutting process, a uniform grid of holes was also precisely patterned across the entire surface, which was drilled after, as shown in Figure III.15. A select few of these holes are dedicated to mounting the board to the supporting structure, while the vast majority serve as a universal fixturing grid, allowing clamps to be placed anywhere on the table to secure differently sized workpieces.

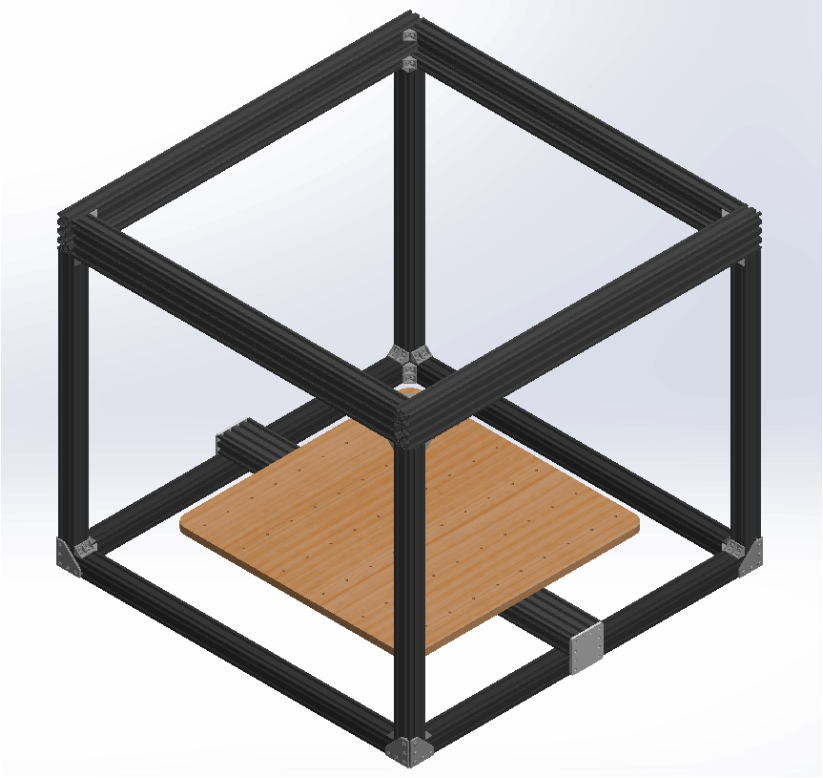
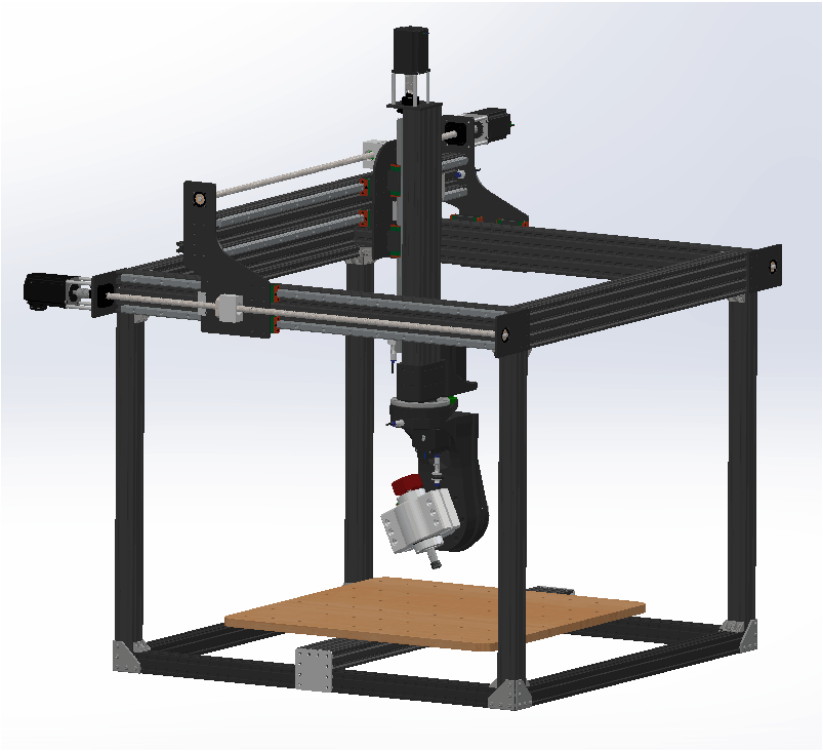


Figure III.15: Machine work table

To elevate the table and integrate it into the machine structure, the wooden plate is supported by a centrally positioned C-beam extrusion mounted directly on top of the lower frame assembly, as shown in Figure III.15. This C-beam acts as the primary structural support of the worktable and helps distribute the machining loads toward the machine base. The beam itself is fixed to the frame using custom laser-cut plexiglass mounting brackets positioned at both extremities. These brackets were designed specifically to ensure proper alignment between the support beam and the frame structure while simplifying the assembly process. The brackets are bolted both to the sides of the C-beam and to the lower aluminum extrusions of the frame using M5 low-profile bolts and drop-in T-nuts compatible with the extrusion system.

Following the integration of the structural frame, the linear drive systems, and the bi-rotary milling head, the mechanical assembly phase of the prototype was successfully concluded. The complete integration of these individual subsystems forms a rigid and precise multi-axis kinematic platform. The fully assembled mechanical structure of the CNC machine is presented in Figure III.16.



(a) Full machine assembly, CAD model



(b) Full machine assembly in real life

Figure III.16: Full machine assembly

III.2 Electrical integration and control hardware

Following the completion of the mechanical assembly, the next stage of the prototype development consists of integrating the electrical and control hardware required to operate the machine. This stage includes the distribution of electrical power, the installation of the control electronics, the wiring of sensors and actuators, and the implementation of the protection and safety elements necessary for reliable machine operation. Unlike the mechanical structure, which defines the physical architecture of the CNC machine, the electrical system is responsible for coordinating motion, transmitting control signals, and supplying power to the different components of the machine.

III.2.1 Power integration

In addition to supplying energy to the different components, the power distribution system must also ensure proper grounding, protection against overcurrent conditions, and sufficient thermal management for continuously operating devices. For this reason, the integration process involves not only selecting suitable power supplies but also organizing the electrical wiring and protection elements in a way that improves reliability and reduces the risk of electrical faults during machine operation.

III.2.1.1 Components power supply

The electrical integration of a CNC system involves the interaction of several subsystems, including motor drivers, controllers, sensors, spindle electronics, and auxiliary devices such as cooling fans and safety switches. Since each component operates under specific electrical requirements, proper power distribution becomes essential to ensure stable operation, reduce electrical noise, simplify maintenance, and improve operational safety. For this reason, the design of the power wiring system must consider not only the voltage and current requirements of each device, but also the physical organization of wiring, protection elements, and electrical connections throughout the machine.

III.2.1.1.1 Stepper motor supply

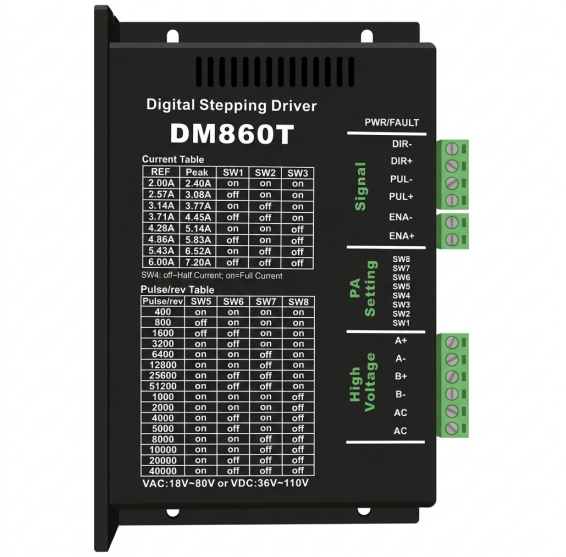
The motion system of the prototype is driven by a total of six stepper motors distributed across the five machine axes. Although the machine operates as a 5-axis CNC system, the X-axis utilizes two independent motors mounted on opposite sides of the frame in order to maintain synchronization and prevent gantry misalignment during movement. The two motors responsible for driving the dual X-axis configuration are closed-loop stepper motors equipped with rotary encoders, while the remaining axes use conventional open-loop stepper motors.

To control these motors, two different categories of drivers were integrated into the electrical system. The encoder-equipped motors are driven using HSS60 closed-

loop stepper drivers, as shown in Figure III.17 (a), while the remaining four motors are controlled through DM860D digital stepper drivers, as shown in Figure III.17 (b). The DM860D drivers support operating voltages ranging from 20–60 VAC or 24–80 VDC, whereas the HSS60 drivers operate within a DC voltage range of 20–50 VDC. To simplify the electrical architecture and maintain compatibility between all motion drivers, a regulated 48 VDC power supply was selected.



(a) HSS60 closed-loop stepper motor driver



(b) DM860D open-loop stepper motor driver

Figure III.17: stepper motor driver used types

The current requirements of the motors were also considered during the sizing of the power system. The selected stepper motors are rated between approximately 2 A and 3 A under nominal operating conditions. For calculation purposes, an average current value of 2.5 A per motor was assumed. In the case of the DM860D drivers, the maximum output current was configured to 2.4 A in order to remain within the safe operating range of the motors while limiting excessive thermal buildup during continuous operation.

Based on the total number of motors, the estimated current demand of the complete motion system reaches approximately 15 A. Consequently, a 48 VDC power supply rated at 15 A was selected, corresponding to a total available power of approximately 720 W. This dedicated supply powers all motion drivers independently from the remaining electronic subsystems of the machine.

To safely distribute this current without introducing excessive voltage drop or overheating in the wiring, the electrical layout was implemented using a parallel branch distribution topology. The selected power supply provides three independent DC output terminals. Instead of routing the entire load through a single power line, the current distribution was divided into three separate branches. Each branch connects one output terminal of the power supply to a WAGO distribution connector, from which the power is further divided toward a pair of motor drivers, as shown in Figure III.18. This hierarchical distribution architecture reduces the current carried

by each individual conductor and helps ensure that all drivers receive a stable and uninterrupted supply voltage during demanding machining operations.

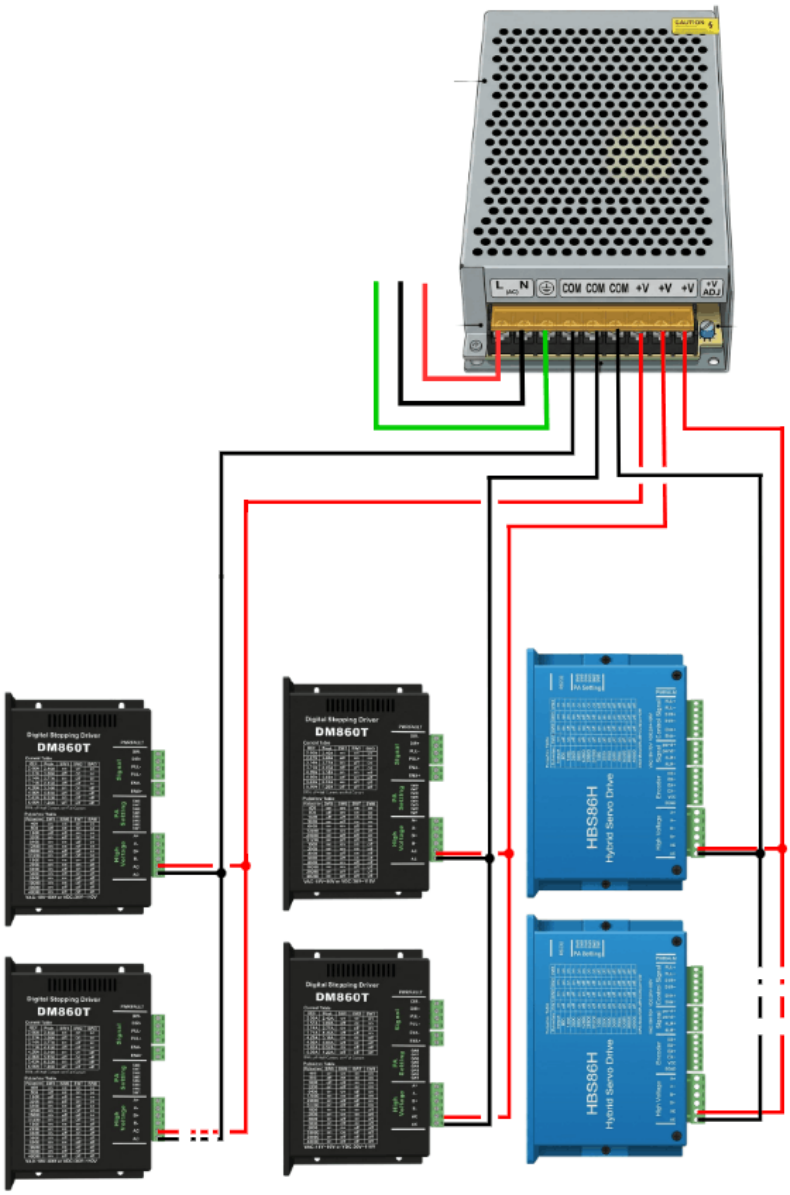


Figure III.18: stepper motors Drivers power connections

III.2.1.1.2 Spindle power supply

The primary cutting tool of this prototype is a 500 W Brushless DC (BLDC) spindle capable of reaching rotational speeds up to 12,000 rpm. Its motion is controlled by a dedicated NVBDL+ brushless motor driver, as shown in Figure III.19, which requires a 48 VDC supply and can support current levels of up to 10 A under demanding operating conditions. This spindle was delivered as part of a complete kit, including its own compatible power supply, which was integrated directly into the electrical system of the machine.



Figure III.19: spindle NVBDL+ driver

Using a dedicated supply for the spindle (as shown in Figure III.20) is an important design choice, since the spindle represents one of the most electrically demanding components of the prototype. By keeping its power circuit separate from the stepper motor supply, the machine reduces the risk of voltage drops and electromagnetic interference. Although the stepper motors also operate from a 48 VDC architecture, the spindle is intentionally isolated from the rest of the drive system in order to improve electrical stability and overall reliability during machining.

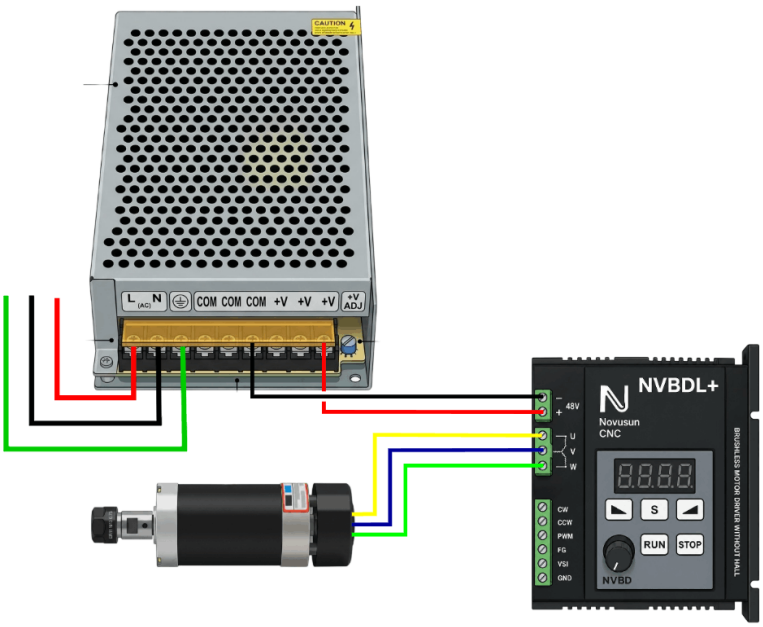


Figure III.20: Spindle driver power connection

Additionally, the spindle is air-cooled, which further simplifies the electrical and thermal integration of the machine. Unlike liquid-cooled spindle systems, it does not

require an auxiliary pump, coolant circuit, or additional power line for circulation equipment. This reduces both wiring complexity and system maintenance while remaining sufficient for the intended operating conditions of the prototype.

III.2.1.1.3 Proximity sensor supply

The inductive proximity sensors used in the prototype are NPN normally open (NO) sensors rated for an operating voltage range of 6–36 V. Unlike mechanical limit switches, these sensors are active electronic devices and therefore require a continuous supply current in order to generate the electromagnetic field used for metal detection. In the present configuration, each sensor draws approximately 15 mA under normal operation, while the output stage can support a switching current of up to 300 mA depending on the load connected to the sensor output. Since the controller input in this prototype only draws around 5 mA, the effective current demand remains very low. Even if all five sensors were triggered simultaneously, which is not expected during normal homing since the axes are referenced sequentially, the total current consumption would remain well below the capacity of a small auxiliary supply.

For this reason, a dedicated 12 V, 2 A power supply was used as the primary source for the proximity sensor circuit. However, since the controller operates using 5 V logic-level inputs, the sensor supply voltage was reduced to maintain full electrical compatibility within the control system. Although the selected sensors are NPN-type devices, meaning their output stage pulls the controller input toward ground when activated, operating the sensors at the same logic voltage level as the controller provides an additional level of electrical safety and helps avoid potential incompatibilities or undesired input conditions. Consequently, an LM2596S DC–DC buck converter was integrated to step the 12 V supply down to a regulated 5 V output, as illustrated in Figure III.21. This reduced voltage level remains entirely sufficient for powering all five inductive proximity sensors, as shown in Figure III.22, while ensuring stable operation, reliable signal detection, and safe interfacing with the controller electronics.

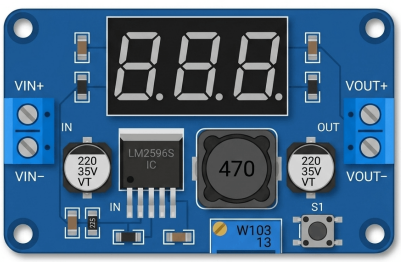


Figure III.21: LM2596S DC–DC buck converter

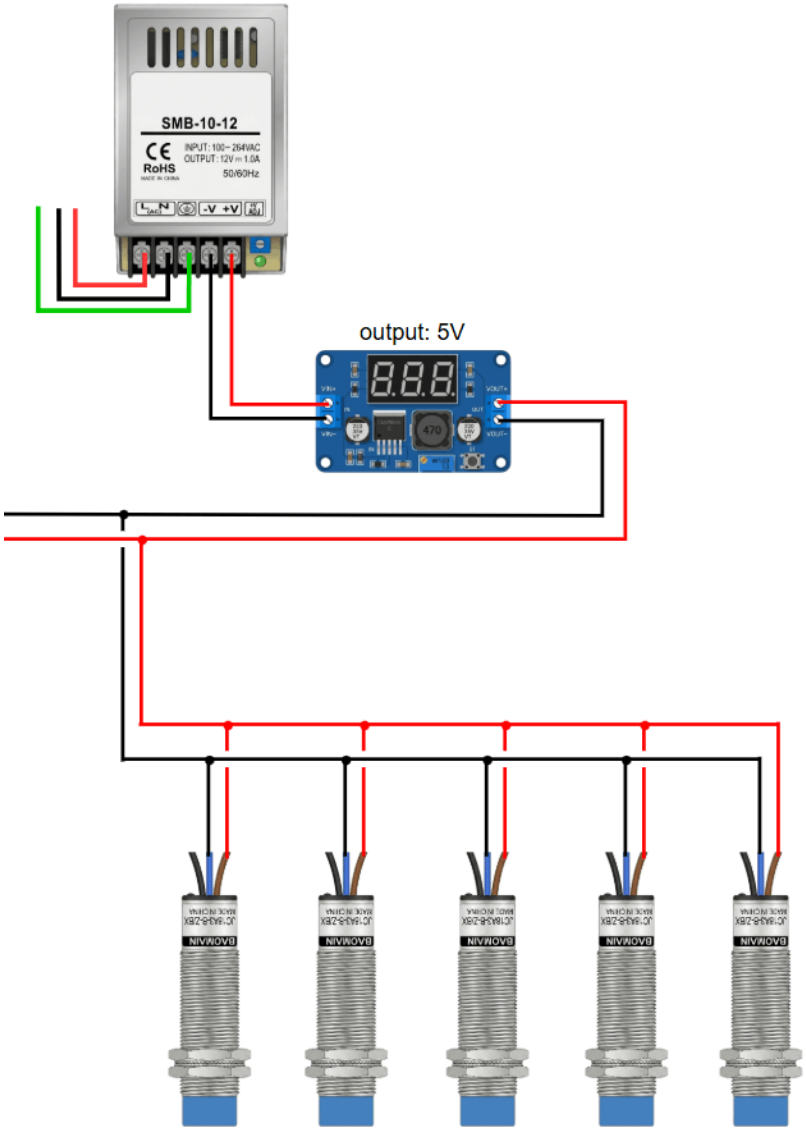


Figure III.22: Proximity sensors power connections

While powering the nominally 6 to 36 V rated sensors at 5 V proved functionally reliable for this prototype, industrial best practices typically advocate operating sensors at a higher voltage (such as 12 V or 24 V) to maximize electromagnetic noise immunity. To safely interface a 12 V sensor with a 5 V controller, galvanic isolation components such as optocouplers or interposing relays are normally employed.

In addition to the supply voltage itself, the electrical reference must remain common between the sensors and the controller so that the output state can be interpreted correctly. Since the NPN sensors use a sinking output configuration, the wiring must be arranged so that the controller input can detect the change in potential reliably when a target is detected. This makes the sensor power supply an important part of the overall control architecture, not only because it energizes the sensors themselves, but also because it establishes the logic conditions required for accurate homing and position detection.

III.2.1.1.4 Controller supply

The motion controller used in the prototype can be powered in two different ways: either directly through the USB connection from the computer or through a dedicated 5 VDC input terminal. In this prototype, the second solution was selected in order to keep the electrical architecture fully integrated inside the cabinet and to maintain a compact and consistent wiring layout. The controller is therefore powered from the same 5 V source used for the proximity sensors, obtained through the LM2596S buck converter, as shown in Figure III.23. Since the controller consumes only about 100 mA, the available 2 A supply is more than sufficient for both the controller and the sensor circuit.

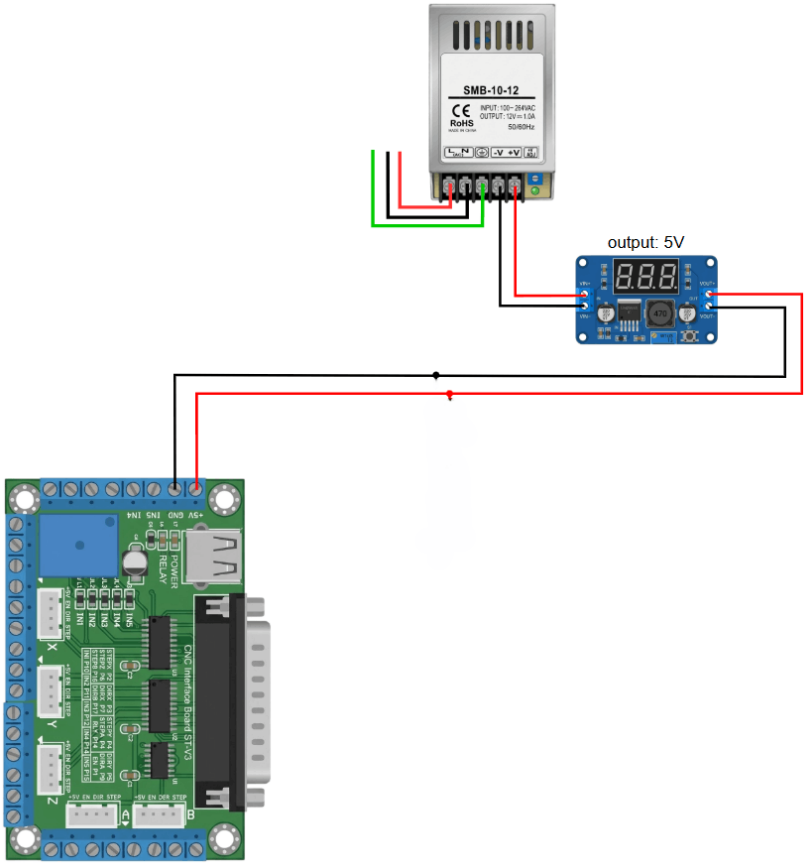


Figure III.23: Controller power connection

This arrangement also simplifies the internal organization of the control cabinet, since it reduces the number of separate power sources required by the low-voltage electronics. In addition, using a regulated shared supply helps maintain compatibility between the controller and the sensor inputs, provided that the common reference ground is properly established throughout the control circuit.

III.2.1.1.5 Cooling fan supply

The control cabinet houses multiple high-draw, heat-generating components, including the 720 W stepper motor power supply, the 500 W spindle power supply, the 12 V auxiliary supply, and the multiple motor and spindle drivers. During continuous

machining operations, these devices release a significant amount of thermal energy. Because the cabinet is a fully enclosed space, this internal heat cannot dissipate naturally. Without forced ventilation, this temperature rise would severely reduce system reliability, shorten component lifespans, and eventually cause thermal interruptions during machine operation. Consequently, active cooling is a mandatory element of the electrical architecture rather than an optional accessory.

To achieve this necessary cooling while protecting the sensitive electronics from the harsh machining environment, the ventilation system was designed to combine thermal exhaust with physical filtration. A filtered air inlet was installed on one side of the cabinet where the fan is placed, while a second filtered opening was placed on the opposite side. This arrangement promotes a controlled, continuous cross-airflow across the components while strictly preventing the direct entry of conductive dust, chips, and other machining debris. By doing so, the ventilation system serves a dual purpose: removing accumulated heat and maintaining a clean internal environment.

To drive this critical airflow, a 220 VAC cooling fan was integrated into the enclosure. Because this fan operates directly on standard alternating current, its electrical integration is relatively straightforward compared to the low-voltage DC control devices. It bypasses the internal DC power supplies entirely and is wired directly into the mains supply block, as shown in Figure III.24. This wiring strategy ensures that the forced ventilation system engages automatically the moment the machine is powered on, guaranteeing continuous thermal management for the long-term stability of the control electronics.

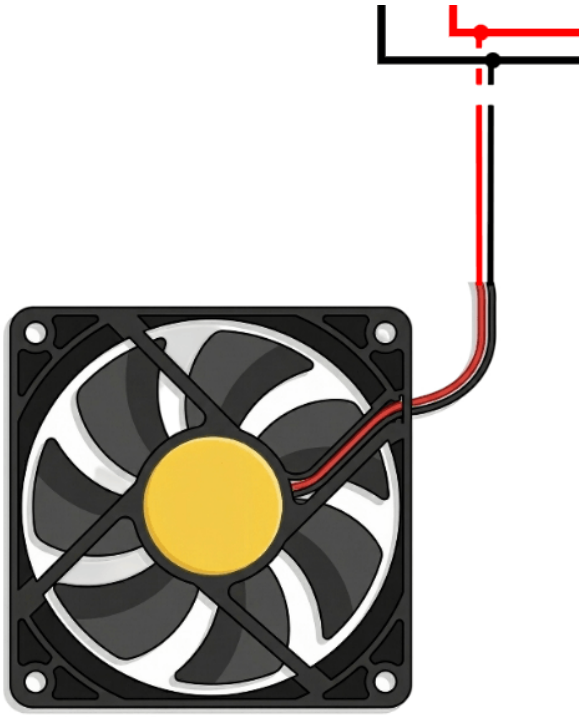


Figure III.24: Cooling fan power connection

III.2.1.2 Safety and protection elements

Because the CNC system draws a relatively high electrical current, the manual ON/OFF buttons and the emergency-stop button are not used to switch the main power directly. Instead, a contactor is employed as the primary power-switching device. The contactor contains an electromagnetic coil connected through terminals A1 and A2, when energized, the internal contacts close and allow the main electrical power to pass to the machine. The contactor used in this prototype is a three-phase unit rated at 9 A under a 380/400VAC AC-3 inductive motor load application.

To verify the physical rating and electrical safety of this component, the maximum current required by the machine's power supplies was calculated by mapping the total Direct Current (DC) load back to the single-phase AC input line. The system utilizes three separate power supplies operating off a 220VAC mains line: a 48V, 15A supply for the stepper motors; a 48V, 10A supply for the spindle; and a 12V, 2A supply for the auxiliary control components. The total DC output power (P_{DC}) is calculated as:

$$P_{\text{DC}} = (48\text{V} \times 15\text{A}) + (48\text{V} \times 10\text{A}) + (12\text{V} \times 2\text{A}) = 1224\text{W} \tag{III.1}$$

Operating from a 220VAC single-phase input supply, the maximum theoretical AC input line current (I_{AC}) drawn by the system is estimated using the standard AC power equation [78, 75]:

$$I_{\text{AC}} = \frac{P_{\text{DC}}}{V_{\text{AC}} \times \eta \times \text{PF}} \tag{III.2}$$

where η represents the operating efficiency and PF represents the power factor of the power supplies. In the absence of specific manufacturer datasheets for the prototype power supplies, empirical industry-standard approximations of 85% efficiency (η = 0.85) and a 0.70 power factor (PF = 0.70) were applied [36, 78]. Substituting these parameters yields:

$$I_{\text{AC}} = \frac{1224\text{W}}{220\text{V} \times 0.85 \times 0.70} \approx 9.35\text{A} \tag{III.3}$$

Although this theoretical maximum running current of 9.35A technically exceeds the nominal 9A AC-3 rating marked on the contactor housing, the device is entirely safe and properly sized for this application. Per international standard IEC 60947-4-1, utilization categories are defined strictly by the electrical behavior of the load connected directly to the contactor's terminals [102]. Because this contactor switches the AC input line of the power supplies, it interacts exclusively with a non-inductive, resistive-capacitive electronic load rather than raw copper motor windings. Consequently, the circuit falls under the AC-1 utilization category.

Manufacturer specifications indicate that a 9A (AC-3) contactor features a conventional free-air thermal current limit (I_{th}) of 20A under AC-1 operating conditions [101]. Furthermore, a multi-axis CNC system practically never demands peak continuous current from all power supplies simultaneously during real-world cutting operations. Upstream circuit protection is reinforced with a 10A fuse socket to isolate short circuits.

The switching of this main contactor is governed by a safer, low-voltage command circuit. This circuit operates at 24 VAC, supplied by a dedicated transformer. The neutral wire of this supply connects directly to the A2 terminal of the contactor coil. The live wire passes successively through the emergency-stop button (NC), the OFF button (NC), and the ON button (NO) before reaching terminal A1. Pressing the ON button momentarily energizes the contactor coil, closing the main power contacts. However, because the ON button is a momentary switch, the coil would immediately de-energize upon release.

To solve this, a latching circuit was implemented. Standard latching requires an auxiliary normally open (NO) contact. Because the machine operates from a single-phase supply, only two of the main contactor channels were needed for the live and neutral conductors. The third unused main phase contact was then repurposed as the auxiliary holding contact. Once the contactor energizes, this contact closes in parallel with the ON push button, creating a self-holding path that continuously supplies the coil. The machine remains powered until the OFF button or the emergency-stop button interrupts the circuit, as illustrated in Figure III.25.

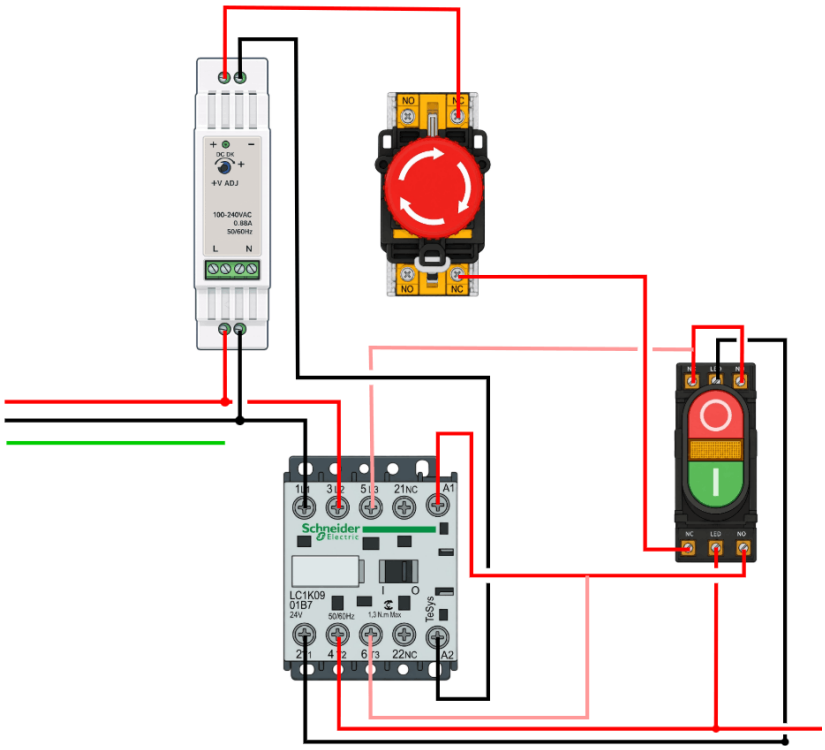


Figure III.25: Safety cicuit

Finally, a complete safety architecture must combine this electrical isolation with software interruption [8]. Simply removing power from the actuators is not always sufficient; if the machining program remains active inside the controller, the machine could unexpectedly resume operation as soon as the emergency-stop circuit is released. To prevent this hazard, the emergency-stop button contains both Normally Closed (NC) and Normally Open (NO) contacts. While the NC contact breaks the hardware command circuit, the NO contact is connected to one of the controller inputs. Because the controller inputs feature internal pull-up resistors, the signal is

pulled to ground when the emergency button is activated [24], notifying the software of the critical stop condition.

Ideally, the CNC controller should possess an independent power supply to safely process software terminations during an emergency stop. In this prototype, the controller's main power supply is routed downstream of the primary contactor, meaning an emergency stop successfully severs its primary power. However, the Mach3 software still reliably registers the emergency halt command. This phenomenon is attributed to parasitic power (backfeeding) supplied via the active 5V logic lines of the PC's parallel port. Because the computer remains powered, its parallel port provides residual voltage through the breakout board's internal protection diodes—evidenced by a dimly lit power LED on the unpowered board. Coupled with an active-low (sinking to ground) emergency switch configuration, this parasitic logic voltage is sufficient for the hardware to securely communicate the severed connection, successfully triggering a software abort in Mach3 despite the loss of main system power.

To synthesize the electrical power distribution architecture detailed in the preceding subsections, a comprehensive power schematic was developed. This diagram illustrates the complete energy routing, from the 220 VAC mains inlet and primary safety contactor through to the individual DC switching supplies, transformers, and step-down converters. Mapping these connections provides a clear overview of how the high-current demands of the drive systems and the low-voltage requirements of the logic components are safely and efficiently satisfied. The complete power distribution diagram for the control cabinet is presented in Figure III.26.

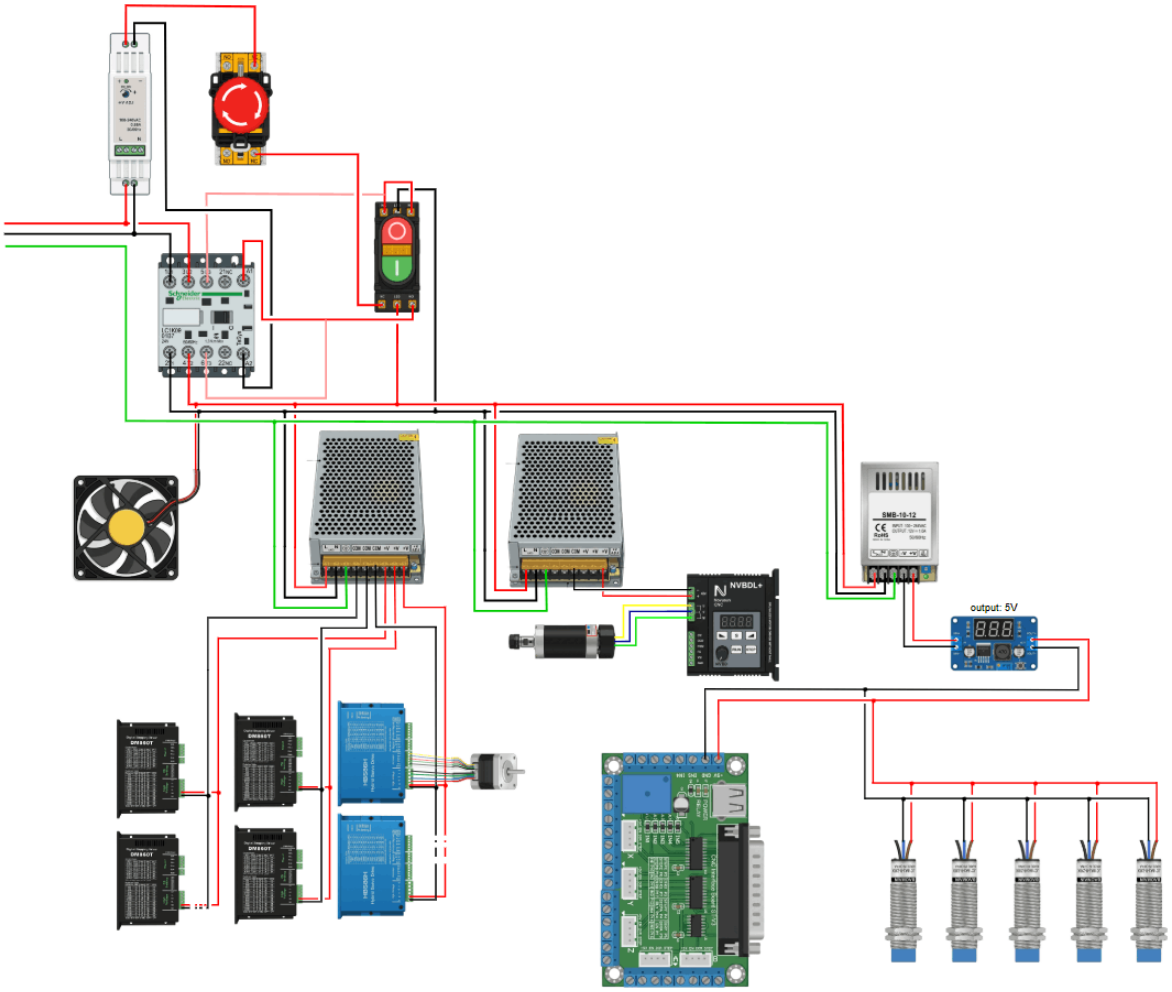


Figure III.26: Power distribution diagram

III.2.2 Input and output signals

The motion control architecture relies on a continuous exchange of low-voltage signals between the ST-V3 controller, as shown in Figure III.27, the physical machine peripherals, and the control software. This communication network is strictly divided into two categories: input signals, which provide the controller with environmental and safety data, and output signals, which translate the software's commands into physical machine actions. The reliable transmission of these 5 V logic signals is critical, as any electrical noise or signal degradation could result in lost positioning or unsafe operating conditions.

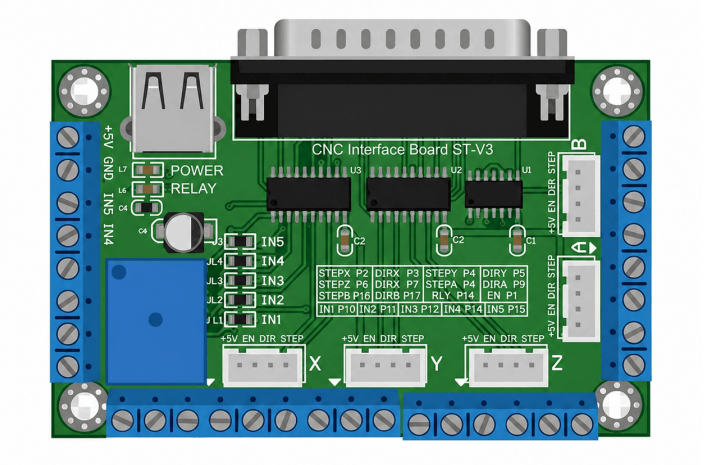


Figure III.27: ST-V3 Breakout board

The input signal network on the ST-V3 controller is designed using an active-low logic configuration. The controller's input pins feature integrated internal pull-up resistors, maintaining a default logic HIGH state (5 V). To register a signal, an external peripheral must sink this voltage, pulling the input pin down to Ground (0 V). This configuration inherently dictates the electrical wiring strategy for both the safety and homing peripherals.

III.2.2.1 Inputs

The input signals section covers the elements used to inform the control system about the state of the machine. In this prototype, the main input devices are the homing sensors and the emergency-stop button, both of which provide essential feedback for safe initialization and operation. These signals are interpreted by the controller as low-voltage digital inputs, which means that their wiring must be consistent with the controller logic and with the electrical characteristics of the selected sensors and switches.

III.2.2.1.1 Sensors

The input signal network on the ST-V3 controller is designed using an active-low logic configuration. The controller's input pins feature integrated internal pull-up resistors, maintaining a default logic HIGH state (5 V). To register a signal, an external peripheral must sink this voltage, pulling the input pin down to Ground (0 V). This configuration inherently dictates the electrical wiring strategy for both the safety and homing peripherals.

To establish the machine's absolute coordinate system, the prototype utilizes NPN Normally Open (NO) inductive proximity sensors on all five axes. Because they are NPN devices, their output perfectly matches the controller's active-low requirement; upon detecting a metal target, the sensor connects the signal line directly to Ground. While the machine features five independent axes, allocating a dedicated controller input for each sensor is inefficient. Because the machine is configured to

execute a sequential homing routine (referencing one axis at a time), the controller only expects a homing signal from the specific axis currently in motion. Taking advantage of this logic, the NO sensors were grouped and wired in parallel [24]. The sensors for the dual-drive X-axis and the Y-axis share a single input pin, the Z-axis sensor occupies a second independent pin, and the A and C rotary axes share a third, as shown in Figure III.28. This parallel grouping successfully communicates all five boundaries while only consuming three physical input terminals, leaving the remaining inputs available for future expansion.

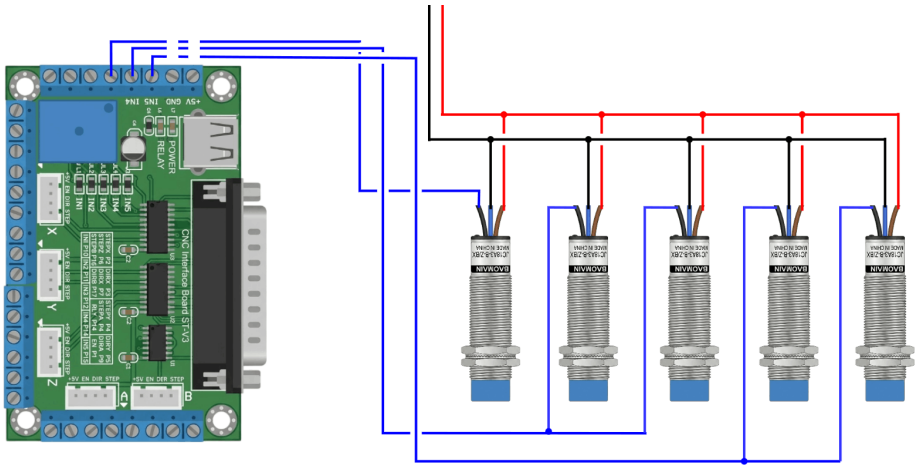


Figure III.28: Proximity sensors wiring to BoB

From an electrical routing perspective, industrial best practices dictate that sensor signals should be transmitted via shielded cables and routed physically apart from high-current DC lines to prevent Electromagnetic Interference (EMI). However, due to prototype constraints, standard unshielded cables were utilized, and the signal lines were routed within the same cable management chains as the 48 V stepper motor power lines. Despite this lack of shielding, experimental testing confirmed that the 5 V active-low logic was robust enough to resist environmental electrical noise, executing the sequential homing routine reliably without registering false triggers.

III.2.2.1.2 Emergency button

The Emergency Stop (E-Stop) button serves a dual purpose: interrupting the main hardware power and triggering a software halt. To achieve this, the Normally Open (NO) terminal of the E-Stop is integrated into the controller's input network. One side of this NO contact is wired to a dedicated ST-V3 input pin, while the other is connected to the common system Ground. During normal operation, the controller's internal pull-up resistor holds the input at 5 V. When the E-Stop is struck, the NO contacts close, instantly pulling the input pin to Ground. This alerts the software to immediately abort the active G-code execution.

III.2.2.2 Outputs

While the input network gathers physical data, the output network is responsible for translating the digital machining trajectories generated by Mach3 into physical kinetic energy. The ST-V3 controller manages this by transmitting precise, low-voltage control signals to the intermediate drive components, specifically the stepper motor drivers and the spindle driver.

III.2.2.2.1 Stepper motor control

The communication between the ST-V3 controller and the six stepper motors is mediated by the motor drivers. The controller does not supply power to the motors directly, instead, it sends logic-level signals to instruct the drivers on how to distribute the 48 V power. These instructions are transmitted via three primary signal channels: Pulse/Step (PUL), Direction (DIR), and Enable (ENA).

To protect the controller from voltage spikes, industrial stepper drivers feature optically isolated inputs. This means the signal wires power internal LEDs within the driver, requiring a complete circuit for each signal. Consequently, the driver inputs feature both positive and negative terminals (e.g., PUL+ and PUL-). There are two standard wiring topologies to complete these circuits: Common Cathode (tying all negative terminals to Ground) or Common Anode (tying all positive terminals to a 5 V source).

For this prototype, the Common Anode topology was selected. The PUL+, DIR+, and ENA+ terminals on all drivers were shunted together and wired to the 5 V output provided on the ST-V3 axis terminal blocks. The corresponding negative terminals (PUL-, DIR-, ENA-) were individually wired to their respective signal pins on the controller, as shown in Figure III.29. In this active-low configuration, the controller generates steps by sinking the current to Ground, which provides a highly reliable switching action for the optocouplers.

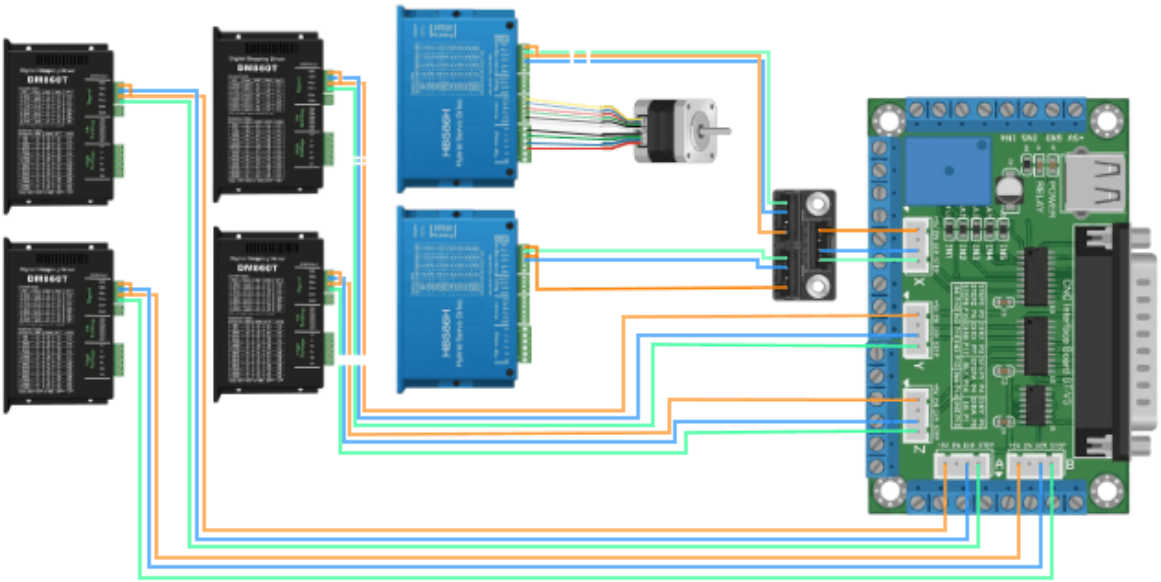


Figure III.29: Stepper motor drivers wiring to BoB

A unique electrical integration challenge arose from the machine's dual-drive architecture: the prototype requires six stepper motors in total, yet the ST-V3 board is strictly a 5-axis controller equipped with only five motor output channels. A standard industrial approach to synchronizing a dual-motor gantry (such as the prototype's X-axis) is to utilize the axis-slaving feature within the Mach3 software. However, software slaving necessitates routing the secondary signal through a spare, independent motor output on the controller. Because all five available controller outputs were permanently allocated to the primary kinematic axes (X, Y, Z, A, and C), software slaving was impossible. To resolve this hardware limitation, a parallel signal divider was implemented, as shown in Figure III.30. The X-axis PUL and DIR logic signals generated by the controller are routed into the hardware splitter, which cleanly duplicates the 5 V pulses and distributes them simultaneously to both X-axis drivers. This hardware-level mirroring provided the most practical and efficient solution, guaranteeing perfectly synchronized gantry movement without requiring an upgrade to a more complex 6-axis controller.

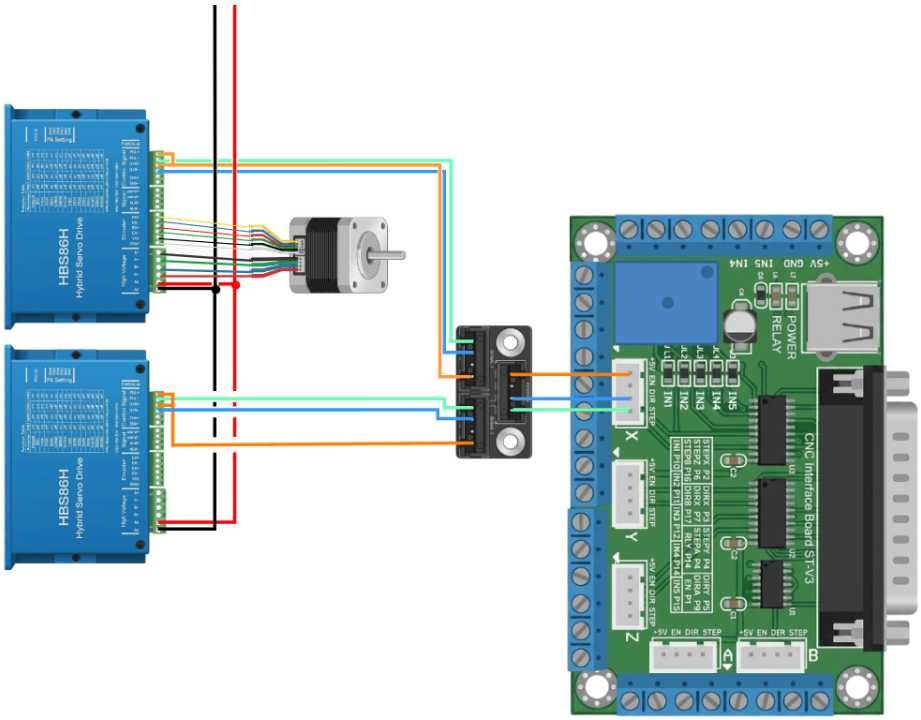


Figure III.30: X-axis stepper motors signal divider

On the output side of the drivers, the heavy-gauge motor power cables are connected to the A+, A-, B+, and B- terminals to energize the two internal motor coils. Furthermore, for the two closed-loop stepper motors installed on the X-axis, the six additional encoder feedback wires were routed directly back into their respective HSS60 drivers. This ensures that the closed-loop drivers can independently monitor their physical position and instantly correct any skipped steps without requiring the ST-V3 controller to process the high-speed encoder data.

III.2.2.2.2 Spindle Control

The spindle control architecture requires managing two distinct parameters: the activation state (ON/OFF) and the rotational velocity (RPM).

To manage the activation state, the ST-V3 controller utilizes an onboard mechanical relay, featuring Common (COM), Normally Open (NO), and Normally Closed (NC) terminals. This relay is manipulated by the Mach3 software via the M3 (Clockwise Spindle Start) and M5 (Spindle Stop) G-code commands. The COM terminal of the relay was tied to the controller's Ground, as shown in Figure III.31, establishing a shared electrical reference with the NVBDL+ spindle driver. The NO terminal was then connected to the Clockwise (CW) input on the spindle driver. Because the NVBDL+ driver utilizes active-low inputs, closing the controller relay connects the CW pin to Ground, successfully activating the spindle. While this configuration only permits Clockwise rotation, standard CNC milling tools are exclusively designed for right-hand cutting, making Counter-Clockwise (CCW) rotation unnecessary for the intended machining operations.

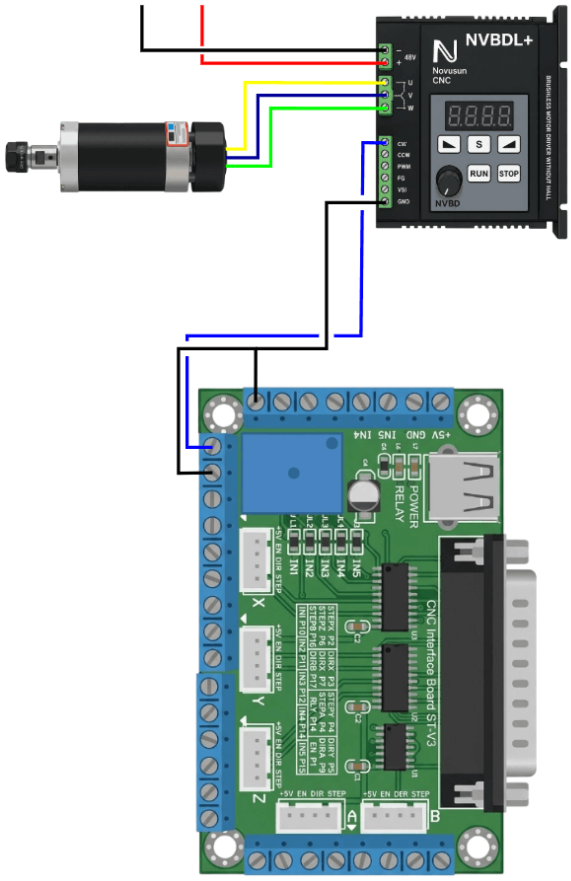


Figure III.31: Spindle NVBDL+ driver wiring to BoB

The spindle speed is managed by the NVBDL+ driver, which can operate through PWM input, VSI analog input, or manual potentiometer control. Since the controller used in this prototype does not provide a dedicated 0–10 V analog output, spindle speed was adjusted manually using the potentiometer after the relevant panel

parameters were configured. This solution keeps the implementation simple while still providing reliable speed control for the spindle system. [87]

Building upon the power distribution framework, the low-voltage communication network serves as the central nervous system of the machine. To provide a complete overview of this logic architecture, a comprehensive control wiring schematic was generated. This diagram details the exact routing of all input signals—including the parallel homing sensors as well as the precise output trajectories of the step, direction, and spindle activation commands from the ST-V3 controller to their respective drivers. The complete signal and control wiring diagram for the electrical cabinet is illustrated in Figure III.32.

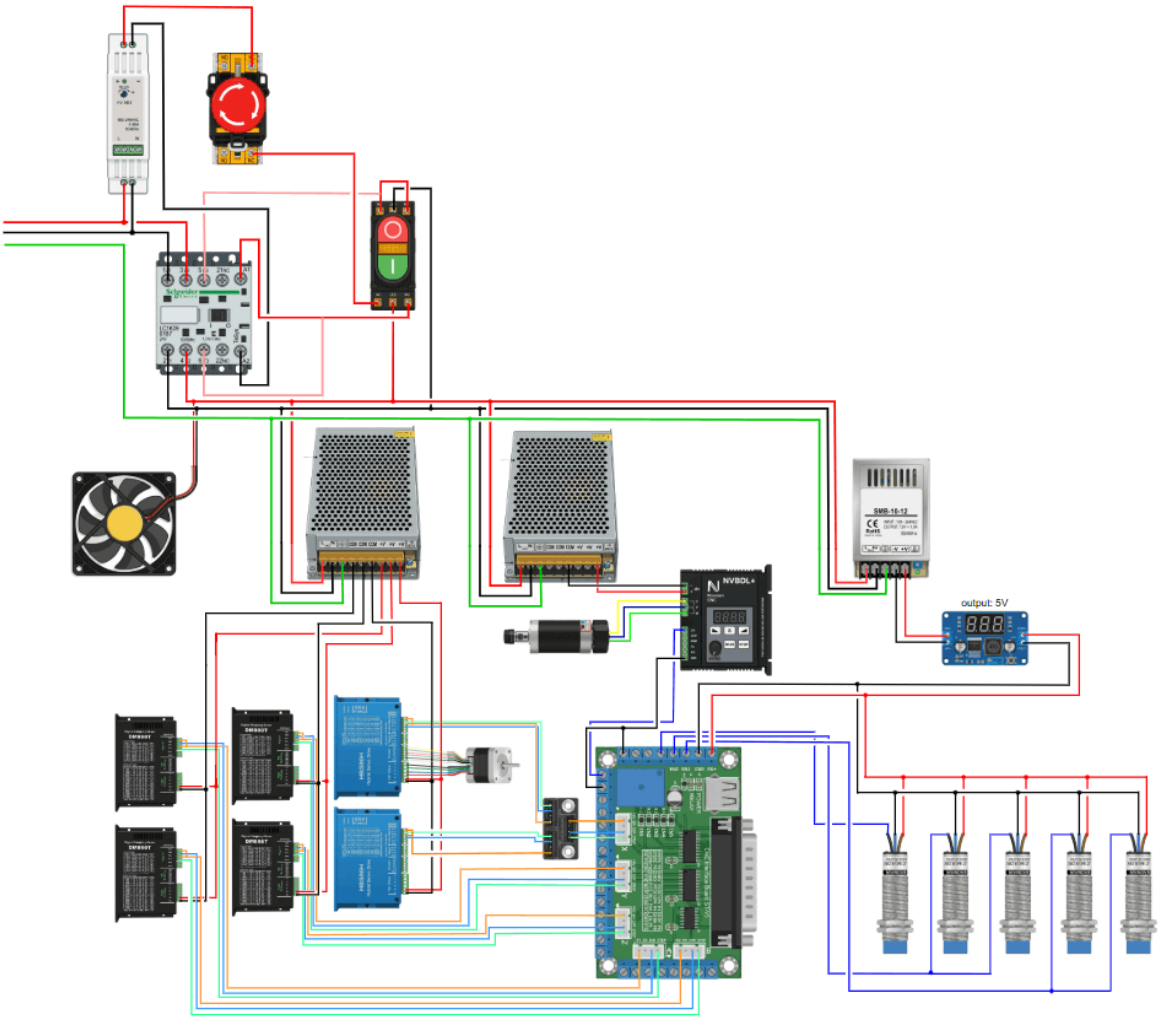


Figure III.32: Control wiring diagram

III.2.3 Cable management and routing

In a multi-axis CNC architecture, the dynamic routing of electrical cables is just as critical as the static wiring. The cable management system must protect the conductors from physical abrasion, prevent entanglement with moving kinematics, and manage the mechanical fatigue induced by continuous flexing. Furthermore, it

must establish a clear physical boundary between the static internal environment of the control cabinet and the dynamic external environment of the machine frame.

To establish this boundary, the transition from the electrical cabinet to the external machine was executed using panel-mounted circular connectors, as shown in Figure III.33. The engineering justification for this approach is twofold: system modularity and environmental sealing. First, hardwiring the machine directly into the control cabinet makes transport, maintenance, and troubleshooting highly restrictive. By terminating all external connections at a centralized bulkhead panel, the entire electrical cabinet can be rapidly and completely disconnected from the mechanical frame. Second, simply passing cables through drilled holes in the cabinet chassis compromises the enclosure's integrity, allowing conductive dust and machining debris to be drawn inside by the cooling fan. The circular connectors provide a sealed physical barrier that maintains the cabinet's ingress protection. Connectors with 3, 4, and 6 pins were selected to correspond to the conductor counts of the spindle/sensors, the standard stepper motors, and the closed-loop encoder signals, respectively. Inside the cabinet, the wiring was arranged using DIN rail organization, especially for the power cables, while the remaining low-current wires were routed in a conventional manner using multicore cables with an appropriate AWG size to avoid heating and excessive voltage drop. This separation between power and signal lines helps reduce electromagnetic interference and improves the overall clarity of the electrical layout.

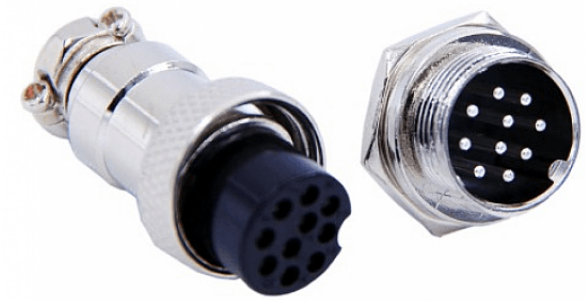
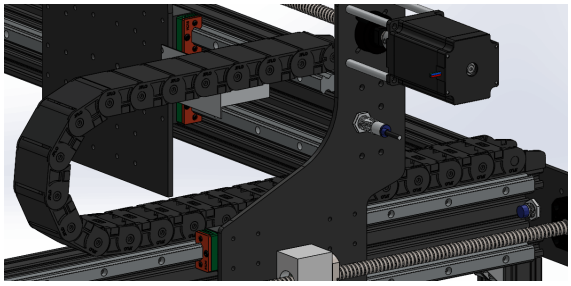


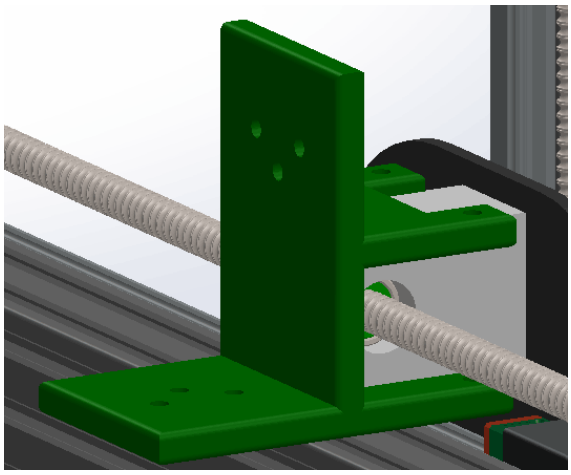
Figure III.33: Circular Aviation connections

For the external routing along the linear kinematics, articulating cable drag chains were implemented to control the cable trajectories and enforce a safe minimum bend radius, thereby preventing internal wire fatigue. The X-axis chain was mounted directly parallel to the dual-drive gantry to accommodate longitudinal movement, as shown in Figure III.34 (a). For the Y and Z axes, a custom 3D-printed junction bracket, as shown in Figure III.34 (b), was designed and mounted directly to the Y-axis ball screw nut housing. This bracket serves as a centralized dynamic anchor

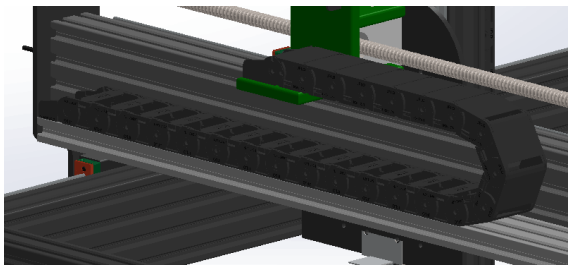
point. The Y-axis drag chain, supported from below by a dedicated aluminum extrusion, terminates at this bracket, as shown in Figure III.34 (c), while the Z-axis chain originates from the same bracket, routing the cables vertically to accommodate the plunge movements of the milling head, as shown in Figure III.34 (d).



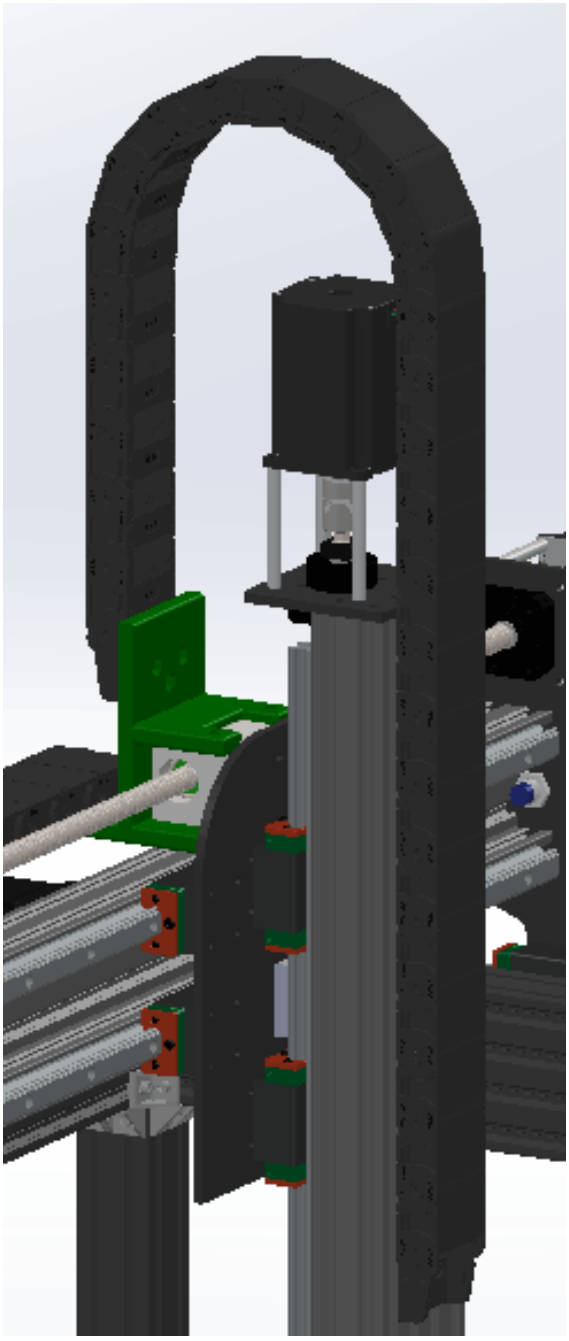
(a) X-axis cable drag chain



(b) Y and Z axes cable drag chain end support



(c) Y-axis cable drag chain



(d) Z-axis cable drag chain

Figure III.34: Linear axes cable management systems

The rotary A and C axes, however, were not fitted with a dedicated drag chain. This was a limitation of the current prototype design, since cable routing for the dual rotary head was not integrated early enough into the mechanical concept. As a result, the cables are held with a spiral wrap, but they may still be exposed

to interference from the moving head during machining. Although this solution is acceptable for validation purposes, a future improvement would be to add a dedicated cable management system for the rotary head (like the Igus RBR chains shown in Figure III.35) in order to improve safety, reliability, and motion freedom.

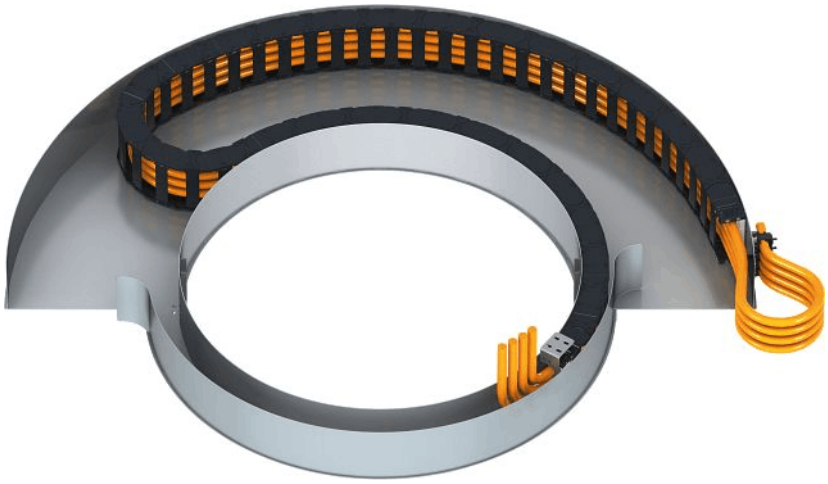


Figure III.35: Igus RBR (Reverse Bend Radius) chains

III.2.4 Electrical cabinet layout

The electrical cabinet shown in Figure III.36 was arranged to maximize spatial efficiency, simplify maintenance, and protect the control electronics from electrical noise and dust. Rather than mounting the devices directly on the enclosure walls, the internal components were fixed to a rigid metal base plate installed at the bottom of the cabinet. This approach improves mechanical stability and makes it easier to position the devices accurately during assembly. To guide the layout before drilling, the plate was first covered with tape and used as a drilling template, which allowed the component positions to be marked, center-punched, and machined with better precision.

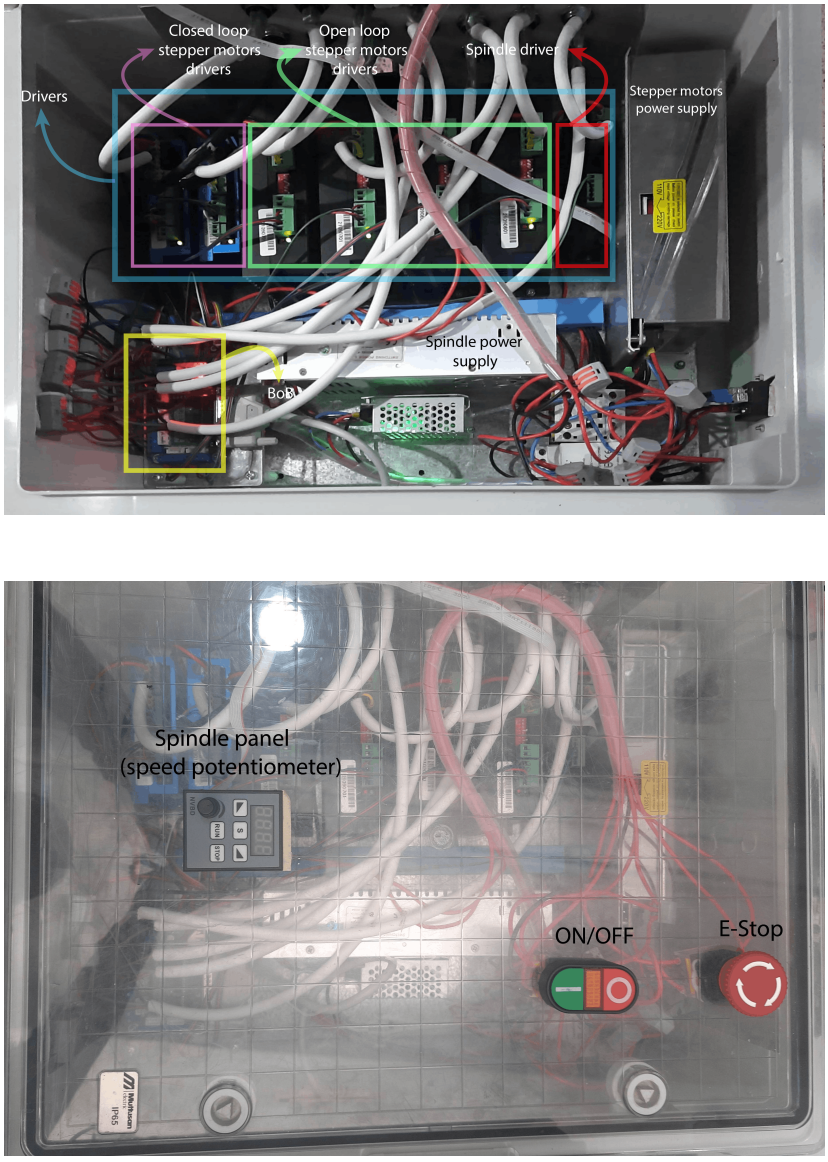


Figure III.36: Cabinet layout

The internal arrangement of the cabinet was organized according to the electrical function of each component. The motion controller is located in the lower-left area of the cabinet, where it is mounted on a transparent plexiglass plate supported by threaded spacers. This tiered arrangement was chosen to save space and allows the LM2596S 5 V buck converter to be placed directly beneath the controller. On the opposite side, the high-voltage mains section is concentrated in the lower-right area. The main AC input enters the cabinet through a side cutout and feeds the safety circuit, while the 24 VAC command transformer and the main contactor are mounted next to each other on a dedicated DIN rail segment. This separation keeps the raw AC wiring short and confines the high-voltage section to a limited part of the cabinet.

The central and upper regions are reserved for the DC power supplies and drive electronics. The 48 V stepper supply and the independent spindle supply are installed across the middle of the cabinet, while the six stepper drivers, the two HSS60 units and the four DM860D units, together with the spindle driver, are

mounted above them. To distribute the power cleanly, WAGO connectors were used to split the DC lines into separate branches. The high-current wires are routed through a horizontal DIN rail cable duct, which helps keep the wiring organized and protected. In contrast, the low-voltage logic wires are kept separate from the power lines and routed more directly in order to reduce electromagnetic interference.

Thermal management was also considered in the cabinet design. A 220 VAC cooling fan was installed beside the driver area to remove the heat generated by the power supplies and motor drivers during operation. In addition, ventilation openings were created in the other part of the enclosure, and filtered vents were added to limit dust ingress while still allowing air to circulate. This arrangement helps maintain a stable internal temperature without compromising the protection of the cabinet against debris. An opening was used for the DB25 cable connected to the controller, with the intention of later replacing it with a sealed bulkhead connector if needed.

The external machine connections are handled through a series of circular aviation connectors mounted on the upper face of the cabinet. Their position was selected to keep the cable paths short. This improves the clarity of the wiring layout and makes the cabinet easier to disconnect from the machine when maintenance or transport is required. Finally, the transparent hinged door of the cabinet was modified to host the main control elements, including the emergency-stop button, the ON/OFF push buttons, and the NVBDL+ spindle driver panel. Mounting the spindle interface on the door allows the operator to access the speed adjustment and RPM display directly, without opening the cabinet during operation.

III.3 Software and control implementation

With the mechanical architecture fully assembled and the electrical power and signal networks safely integrated, the physical foundation of the 5-axis CNC prototype is complete. However, to transform this static hardware into a dynamic, automated manufacturing system, a digital control interface must be established. The subsequent phase of development focuses on the fundamental configuration of the control software, the physical calibration of the kinematic axes, the development of the CAM post-processor for the bi-rotary head, and the final operational validation of the complete mechatronic system.

III.3.1 Mach3 control software configuration

After the hardware assembly and electrical integration were completed, the CNC prototype was configured in Mach3 in order to define the machine units, establish communication with the controller, assign the input and output signals, and tune the motion parameters of each axis. This software setup is essential because it connects the mechanical behavior of the machine to the control logic used during operation. In practice, the quality of the Mach3 configuration directly influences the accuracy, safety, and smoothness of the machine motion.

III.3.1.1 Machine units and coordinate system

The first step in the configuration process was the selection of the metric unit system. The machine was set to operate in millimeters (mm), which is consistent with the dimensions used in the mechanical design, the CAD model, and the CAM toolpaths. This selection was made through the "`Select Native Units`" dialog box in Mach3, as shown in Figure III.37, ensuring that all axis positions, feeds, and motion parameters would be interpreted in a single coherent unit system. Using the same unit convention throughout the entire workflow is critical because it prevents conversion errors and simplifies the interpretation of machine coordinates during setup and operation.

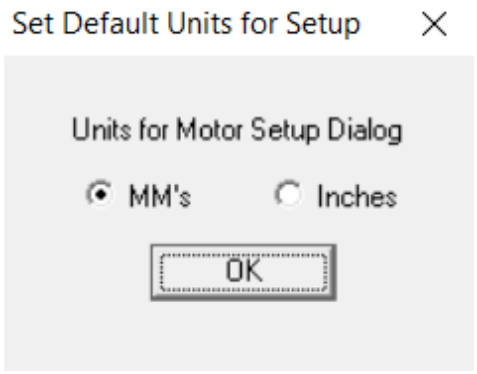


Figure III.37: Selection of the metric unit system

III.3.1.2 Communication setup

Mach3 communicates with the ST-V3 breakout board (BoB) through a parallel-port (LPT) interface. Although the parallel port is an older interface originally used for printers, it remains an industrial standard in many CNC control systems because it provides a direct, low-latency method to transmit step and direction signals without the buffering delays common to standard USB protocols. Although alternative solutions exist (such as the UC100, a dedicated USB to parallel motion controller), they were not adopted in this case due to budget and local availability constraints. In this prototype, the controller was connected to the PC through a DB25 parallel cable. The port address was configured in the "`Ports and Pins`" setup window, as shown in Figure III.38, after enabling Port 1, which is the only port required for this machine.

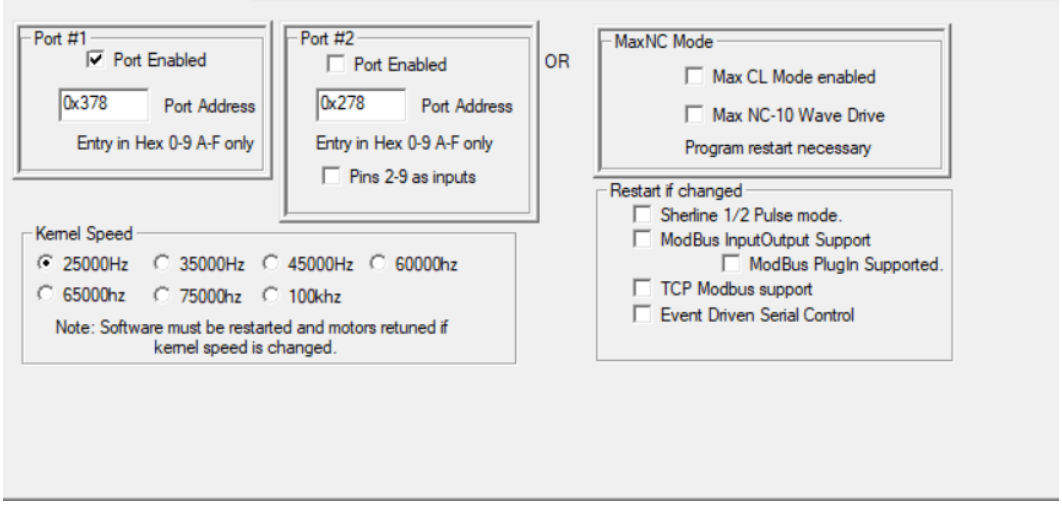


Figure III.38: Port selection

The kernel speed was set to 25 kHz, which defines the maximum frequency at which Mach3 can generate motion pulses for the controller. This parameter has a direct influence on the maximum achievable axis speed and the resolution of the motion system, which is talked about in more detail later in this section. Because the free version of Mach3 imposes a hard limitation on the available kernel speed, this value cannot be increased further.

III.3.1.3 Motor output configuration

The motor output configuration was defined in the `"Motor Outputs"` tab of the `"Ports and Pins"` menu, as shown in Figure III.39. In this prototype, all used axes were enabled, namely X, Y, Z, A, and C, together with the spindle output. For each axis, the corresponding step and direction pins were assigned according to the wiring of the ST-V3 controller. The spindle output was configured separately, since the controller is only used to enable or disable spindle operation through its relay output and does not provide a separate direction signal for spindle rotation.

Signal	Enabled	Step Pin#	Dir Pin#	Dir LowActi...	Step Low A...	Step Port	Dir Port
X Axis	✓	2	3	✓	✓	1	1
Y Axis	✓	4	5	✓	✓	1	1
Z Axis	✓	6	7	✓	✓	1	1
A Axis	✓	16	17	✓	✓	1	1
B Axis	✗	0	0	✗	✗	0	0
C Axis	✓	8	9	✓	✓	0	0
Spindle	✓	14	0	✗	✓	1	1

Figure III.39: Motor output configuration

All axis outputs were configured as active low, which matches the common-anode

wiring method used in the driver inputs. In this arrangement, the positive terminals of the step, direction, and enable signals are tied together to the 5 V reference, while the negative terminals are connected to the controller outputs. This configuration was also applied to the spindle enable signal, since the NVBDL+ driver is activated by a low-level command. Finally, the port number for all motor signals was set to port 1, which corresponds to the selected parallel-port interface. Finally, the port number for all motor outputs was set to Port 1, which corresponds to the parallel-port interface selected for communication with the controller.

III.3.1.4 Input signal configuration

The input signals were configured in the `"Input signals"` tab of the same menu, as shown in Figure III.40. The machine uses homing sensors for the X, Y, Z, A, and C axes, as well as an emergency-stop input. Since the inductive homing sensors are NPN-type devices and the controller inputs include internal pull-up resistors, the active low option was selected for these signals. This means that the input is detected when the sensor pulls the line to ground. The sensors were assigned to the correct port and pin according to the wiring of the machine, with the X and Y sensors sharing one input, and the A and C sensors sharing another, since these axes are homed sequentially rather than simultaneously.

Signal	Enabled	Port #	Pin Number	Active Low	Emulated	HotKey
X ++	✗	0	0	✗	✗	0
X --	✗	0	0	✗	✗	0
X Home	✓	1	10	✓	✗	0
Y ++	✗	0	0	✗	✗	0
Y --	✗	0	0	✗	✗	0
Y Home	✓	1	10	✓	✗	0
Z ++	✗	0	0	✗	✗	0
Z --	✗	0	0	✗	✗	0
Z Home	✓	1	11	✓	✗	0

Signal	Enabled	Port #	Pin Number	Active Low	Emulated	HotKey
A ++	✗	0	0	✗	✗	0
A --	✗	0	0	✗	✗	0
A Home	✓	1	12	✓	✗	0
B ++	✗	0	0	✗	✗	0
B --	✗	0	0	✗	✗	0
B Home	✗	0	0	✗	✗	0
C ++	✗	0	0	✗	✗	0
C --	✗	0	0	✗	✗	0
C Home	✓	1	12	✓	✗	0

Figure III.40: Proximity sensors input signal configuration

The emergency-stop input was also set as active low and connected to the appro-

priate controller pin, as shown in Figure III.41. This configuration ensures that the controller can detect the emergency condition as a grounded input signal. Using the same logic level for both the sensors and the emergency stop simplifies the signal interpretation and makes the input system more consistent. It also matches the wiring strategy used throughout the machine, where low-level signals are interpreted as active commands.

Signal	Enabled	Port #	Pin Number	Active Low	Emulated	HotKey
Input #4	✗	0	0	✗	✗	0
Probe	✗	0	0	✗	✗	0
Index	✗	0	0	✗	✗	0
Limit Ovrd	✗	0	0	✗	✗	0
EStop	✓	1	15	✓	✗	0
THC On	✗	0	0	✗	✗	0
THC Up	✗	0	0	✗	✗	0
THC Down	✗	0	0	✗	✗	0
OEM Trig #1	✗	0	0	✗	✗	0

Figure III.41: E-stop input signal configuration

III.3.1.5 Output signal configuration

The output signal settings were defined in the "`Output Signals`" tab, as shown in Figure III.42. In this configuration, the enable output was activated and assigned to the corresponding driver enable pin so that the controller can permit or disable the stepper drivers when necessary. This function is useful both during startup and during emergency conditions, since it allows the system to stop motion without modifying the motor wiring. The output was also configured as active low to match the wiring used in the driver interface.

Signal	Enabled	Port #	Pin Number	Active Low
Digit Trig	✗	1	0	✗
Enable1	✓	1	1	✓
Enable2	✗	1	0	✗
Enable3	✗	1	0	✗
Enable4	✗	1	0	✗
Enable5	✗	1	0	✗
Enable6	✗	1	0	✗
Output #1	✓	1	14	✓
Output #2	✗	1	0	✗

Figure III.42: Output signal configuration

A second output was assigned to the relay used for spindle control. This relay

output allows Mach3 to activate the spindle driver through the controller interface, even though the spindle speed itself is not controlled directly by the BOB. The relay was assigned to port 1 and configured as active low, in agreement with the logic of the spindle driver and the controller output stage.

III.3.1.6 Motor tuning

Motor tuning is one of the most important steps in Mach3 configuration, since it defines the relationship between the commanded motion and the actual displacement of each axis. The main parameters used in this menu are the steps per unit, the velocity, and the acceleration. The steps per unit define how many electrical pulses are required to move the axis by one millimeter for linear axes or one degree for rotary axes. The velocity and acceleration determine how fast the axis can move and how quickly it can reach the selected speed.

- **Linear axes tuning** For the linear axes, the steps per unit were calculated from the stepper motor resolution, the microstepping setting, and the lead of the ball screw. In this prototype, the motors generate 200 steps per revolution, the microstepping level is 32, and the ball screw lead is 4 mm, which gives:

$$\text{Steps per unit} = \frac{200 \times 32}{4} = 1600$$

This value was used for all linear axes. To define the maximum velocity, two separate constraints were evaluated: the physical hardware limit and the software limit. Mechanically, the NEMA 23 stepper motors can operate reliably up to approximately 1000 RPM. Given the 4 mm lead, the physical maximum linear speed of the hardware is:

$$\text{Physical max speed} = 1000 \text{ RPM} \times 4 \text{ mm/rev} = 4000 \text{ mm/min}$$

However, the maximum theoretical linear speed is severely restricted by the software's kernel frequency of 25 kHz, which limits the pulse output to:

$$\text{Software max speed} = \frac{25000}{1600} = 15.625 \text{ mm/s} = 937.5 \text{ mm/min}$$

This comparison highlights a significant software constraint, where the Mach3 kernel limit restricts the machine to less than a quarter of the motors' physical potential. For this reason, the selected velocity was set to 900 mm/min to remain safely below the software limit and allow some control margin. The acceleration was set to 50, as shown in Figure III.43, which provides a reasonable compromise between responsiveness and mechanical stability.

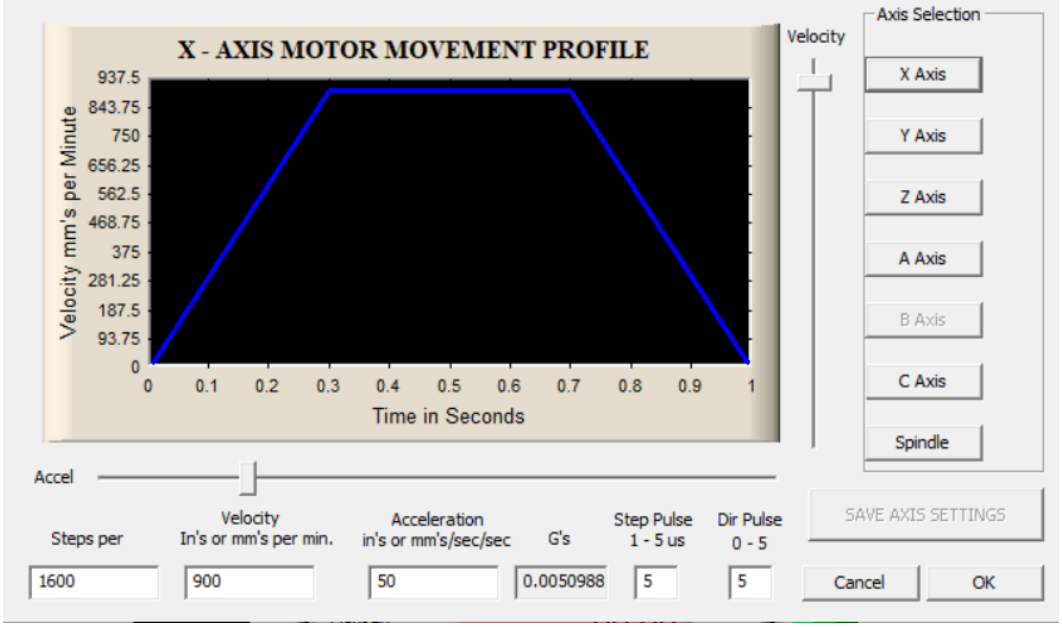


Figure III.43: Linear axes motor tuning

- **Rotary axes tuning** For the rotary axes, the steps per unit depend on the belt reduction ratio instead of a ball screw lead. The motors again use 200 steps per revolution and 32 microsteps, while the pulley ratio is given by:

$$\frac{72}{20} = 3.6$$

The resulting steps per degree are calculated as:

$$\text{Steps per degree} = \frac{200 \times 32 \times 3.6}{360} = 64$$

Evaluating the physical hardware constraint based on the same 1000 RPM motor limit and the 3.6 gear reduction yields a maximum mechanical axis speed of:

$$\text{Physical max speed} = \frac{1000 \text{ RPM} \times 360^\circ}{3.6} = 100000 \text{ deg/min}$$

Conversely, the theoretical rotational speed permitted by the software's kernel frequency is:

$$\text{Software max speed} = \frac{25000}{64} = 390.625 \text{ deg/s} = 23437.5 \text{ deg/min}$$

While the software constraint is still present, both limits are well above the practical and safe operating speeds of the rotary system. To preserve mechanical stability and avoid excessive dynamic loads or vibrations on the bi-rotary head, the selected velocity was conservatively set to 2500 deg/min and the acceleration to 300, as shown in Figure III.44.

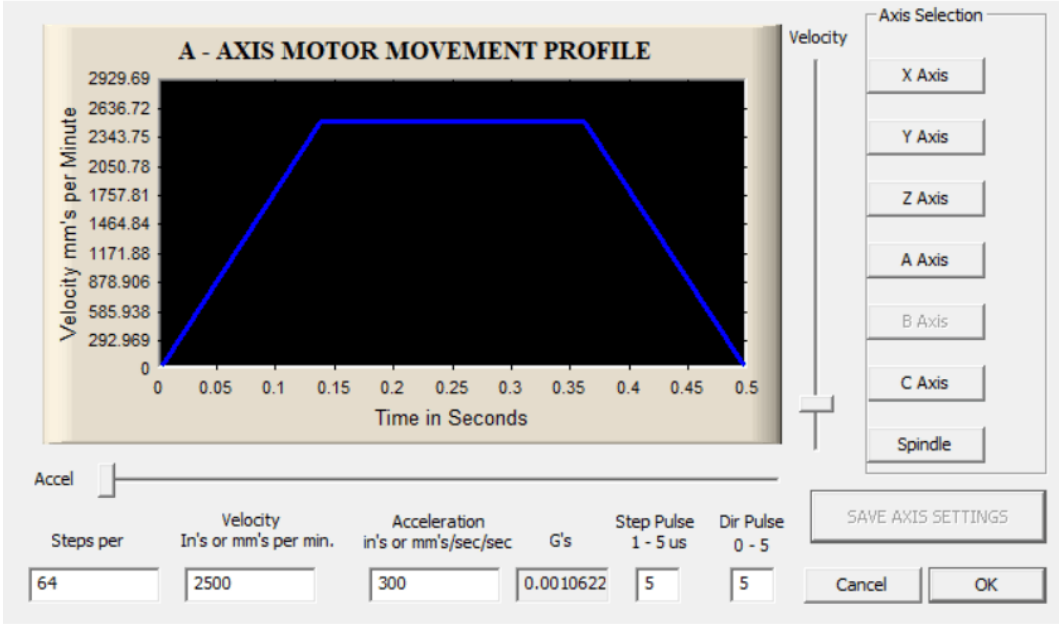


Figure III.44: Rotary axes motor tuning

III.3.1.7 General configuration

The general configuration menu was used to define the basic machine behavior, particularly for the rotary axes. Since the A and C axes are rotational, they were designated as angular axes in Mach3, as shown in Figure III.45. This ensures that the software interprets their motion correctly and applies the appropriate coordinate handling during toolpath execution and manual jogging. Other related parameters, such as rotational soft limits, were also configured through the corresponding settings in the control software.

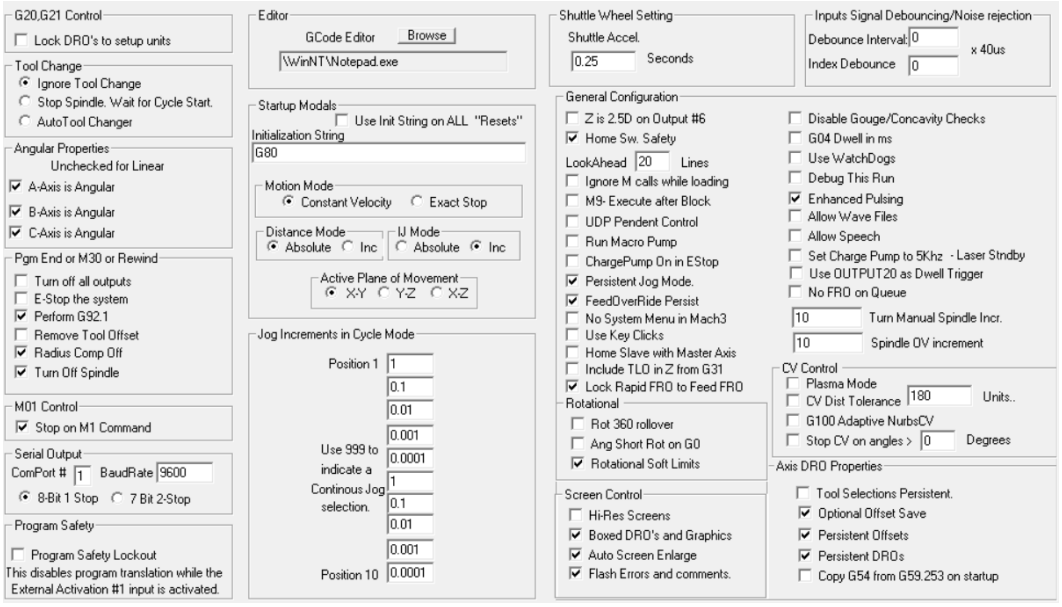


Figure III.45: General configuration

III.3.1.8 Homing and soft limits

The homing and soft limit setup was used to define the reference position of each axis and to prevent the machine from moving beyond its intended travel range. Homing is performed using the inductive sensors installed on the axes, allowing the controller to establish a known machine zero before machining begins. Once homing is completed, Mach3 can calculate the axis positions relative to this reference point.

Soft limits were enabled to protect the machine even though physical end stops were not heavily relied upon. By defining the minimum and maximum travel values for each axis, as shown in Figure III.46, Mach3 can stop the machine before it reaches an unsafe position. This feature is particularly useful in a prototype machine, where the travel range may still be refined during testing. The homing recovery speed was set to a low value, around 20%, so that the axes approach their sensors gently during the reference procedure and do not return too quickly when searching for the home position.

Axis	Reversed	Soft Max	Soft Min	Slow Zone	Home Off.	Home N...	Auto Zero	Speed %
X	✗	650.00	0.00	3.00	0.0000	✓	✓	20
Y	✗	0.00	-550.00	3.00	0.0000	✓	✓	20
Z	✓	0.00	-190.00	3.00	0.0000	✗	✓	20
A	✗	0.00	0.00	0.00	0.0000	✗	✓	0
B	✓	120.00	-120.00	3.00	0.0000	✗	✓	20
C	✓	360.00	-360.00	3.00	0.0000	✓	✓	20

Figure III.46: Homing and soft limits

III.3.1.9 Additional configuration parameters

Other configuration parameters were also adjusted to improve the usability of the software interface. These included hotkeys and general screen-related options that facilitate machine control during operation. Such settings are not directly related to the motion logic itself, but they improve the interaction between the operator and the machine and make the control environment easier to use during testing and development.

III.3.1.10 Unused features

Some Mach3 features were not used in this prototype because they were not required by the machine architecture. In particular, axis slaving was not implemented, since the dual X-axis system was driven by independent motors and managed through its own synchronization strategy. Using slave axes in this case was unnecessary and would not match the chosen mechanical arrangement. As a result, the X-axis remained configured as a dual-drive system without software slaving.

III.3.2 Axis calibration and error compensation

While the theoretical motor tuning parameters provide a functional baseline for machine movement, they rely on the assumption of perfect mechanical components. In reality, manufacturing tolerances, material wear, and assembly imperfections introduce positional errors. To achieve the high dimensional accuracy required for 5-axis milling, the prototype must undergo physical calibration, bridging the gap between theoretical software commands and empirical kinematic movement.

III.3.2.1 Empirical step calibration

The initial calibration phase verifies the linear and rotational accuracy of the axes over discrete distances. While the theoretical "Steps per Unit" were previously calculated mathematically, Mach3 provides an empirical calibration utility located within the `Settings` interface, specifically the `Set Steps per Unit` wizard.

This semi-automated procedure involves commanding an axis to travel a specific nominal distance. A high-precision dial indicator (or digital caliper) is mounted to the machine frame to measure the actual physical displacement of the gantry or spindle. For example, if the software commands a 50 mm positive move, but the dial indicator records 49.85 mm of actual travel, a linear scaling error exists. The operator inputs this true measured value back into Mach3, and the software automatically recalculates and overwrites the theoretical "Steps per Unit" with an empirically corrected value. This procedure has to be repeated iteratively across the X, Y, and Z axes until the commanded travel perfectly matches the physical displacement, nullifying systemic scaling errors.

III.3.2.2 Backlash compensation

A critical mechanical reality in any CNC drive system is backlash, the microscopic mechanical clearance or "play" between the ball screw threads and the ball nut. When an axis reverses direction, the stepper motor must rotate a specific amount just to take up this clearance before the gantry actually begins to move. If left uncompensated, backlash results in flattened circles and dimensional inaccuracies during direction reversals.

To counteract this, the physical backlash of each axis needs to be measured by zeroing a dial indicator against the carriage, moving the axis in one direction, and then commanding a microscopic move in the reverse direction until the indicator registered movement. This measured clearance distance was entered into Mach3's `Backlash Compensation` vector. During operation, whenever an axis reverses trajectory, Mach3 artificially injects high-speed supplemental motor pulses to instantly consume the mechanical clearance, ensuring the physical toolpath remains geometrically true.

III.3.2.3 Lead screw mapping

While empirical step calibration and backlash compensation address linear and reversal errors, they assume that the ball screw pitch is perfectly uniform along its entire length. In reality, ball screws can exhibit localized non-linear pitch variations due to manufacturing defects, thermal expansion, or localized wear.

To achieve Master-level precision, Mach3's advanced `"Screw Mapping"` feature can be utilized. This error compensation method transcends a single global multiplier. Instead, the axis is mapped at discrete, sequential intervals (e.g., every 10 mm) along its entire travel length using a precision reference scale. The deviation at each specific interval is recorded into a digital lookup table within the software. During G-code execution, Mach3 dynamically cross-references the spindle's absolute coordinate against this table, applying localized micro-adjustments to the pulse stream. This dynamic mapping effectively neutralizes complex, non-linear mechanical inaccuracies, allowing a standard ball screw to perform with the precision of a high-end ground screw.

III.3.3 CAM Post-Processing for 5-Axis kinematics

While Mach3 successfully governs the electrical pulses sent to the motors, it does not inherently understand complex 3D geometry. To machine a physical part, a Computer-Aided Manufacturing (CAM) software must generate the toolpaths, and a Post-Processor must translate those toolpaths into the specific G-code dialect understood by the machine's controller.

A post-processor is a highly specialized bridging algorithm. It is never universal; it must be explicitly tailored to three distinct variables: the CAM software generating the data, the controller executing the code (e.g., Mach3 vs. Fanuc), and the exact kinematic architecture of the machine (e.g., Head-Head vs. Table-Table). A post-processor written for a 5-axis trunnion table will instantly crash a 5-axis bi-rotary head machine, even if both run on Mach3, because the rotational pivot math is entirely inverted.

III.3.3.1 CAM software selection

Initially, the CAD modeling for the prototype was executed within SolidWorks. However, native SolidWorks CAM packages are primarily optimized for 3-axis and indexed multi-axis operations (3+2 machining) and lack the robust algorithmic generation required for true, simultaneous 5-axis continuous milling. To resolve this, the workflow was transitioned to SolidCAM, which integrates directly into the SolidWorks environment. SolidCAM provides advanced simultaneous 5-axis trajectory generation and, crucially, offers an accessible architecture for developing and modifying custom post-processors.

III.3.3.2 Post-Processor architecture and modification

Developing a 5-axis post-processor from scratch is a highly complex software engineering task. A more standard industrial approach is to source an existing post-processor designed for a similar machine and modify its parameters. For this prototype, a baseline post-processor was acquired from the "5 Axis Maker" project, which is a commercial desktop CNC that also utilizes a Mach3 controller and a dual-rotary (Head-Head) kinematic architecture.

Within the SolidCAM environment, a post-processor is divided into two distinct, interconnected files: the VMID (Virtual Machine ID) and the GPP (General Post Processor). Both required specific modifications to match the physical reality of the constructed prototype.

- **The VMID File (Kinematic Definition)** The VMID file serves as the digital twin of the machine, defining the structural kinematic tree, axis limits, and rotational orientations. Unlike raw post-processor scripts that require manual editing of thousands of lines of code, the VMID is configured through SolidCAM's Machine ID Editor. This Graphical User Interface (GUI) provides a highly intuitive, visual environment for configuring the machine's mechanical parameters. Several critical modifications were made to this file:
  - **Axis travel limits:** The physical minimum and maximum travel dimensions established during the mechanical build were programmed into the VMID to ensure SolidCAM would not generate toolpaths that exceed the machine's physical envelope.
  - **Kinematic pivot points:** Because Mach3 lacks native Tool Center Point Control (TCPC), the controller cannot calculate 5-axis spatial offsets in real time. Therefore, SolidCAM must pre-calculate the inverse kinematics. To allow this, the exact physical distances from the A and C rotational joint centers to the tool tip (the pivot lengths) were meticulously measured and defined within the VMID kinematic tree.
- **The GPP file (Syntax generation)** While the VMID defines the physical geometry, the GPP file contains the logical scripts that format the raw coordinate data into readable Mach3 G-code text. The acquired GPP file is highly streamlined, consisting of approximately 300 lines of code. This concise structure makes it significantly easier to audit and modify compared to the dense, highly complex post-processor scripts typically found in industrial systems. Modifications to the GPP focused on hardware-specific command outputs:
  - **Spindle control logic:** As established in the electrical configuration, the ST-V3 controller cannot dynamically regulate the NVBDL+ spindle driver's RPM via software. Therefore, the GPP was modified to output a fixed, nominal spindle speed value whenever the M3 (Clockwise) command is triggered. This ensures that SolidCAM's internal feed-and-speed algorithms can still calculate accurate chip loads based on the manually selected physical RPM, without generating unsupported PWM commands in the final G-code.

- **Rotary syntax:** The formatting of the A and C angular outputs was verified to ensure Mach3 interprets the rotational degrees correctly without adding erroneous supplementary axes (such as B).

This post-processing stage is what makes the CAM output usable on a custom machine. Without it, even a correct toolpath would still be too generic to run safely on a CNC machine. By combining the machine definition stored in the VMID with the G-code generation logic in the GPP file, the CAM output can be matched to the actual kinematics, controller behavior, and spindle-control limits of the machine. For this reason, post-processing is not a minor formatting step, but a key link between digital machining and real machine execution.

Conclusion

This chapter presented the physical realization of the 5-axis CNC prototype, describing the transition from the theoretical design stage to a complete mechanical and electronic assembly. The construction process brought together the main structural elements of the machine, including the rigid frame, the linear motion systems of the X, Y, and Z axes, the worktable, and the custom bi-rotary head responsible for the A and C axes. Particular attention was given to the alignment and mounting of the different subsystems, since the accuracy and rigidity of these mechanical junctions directly determine the ability of the machine to maintain stable motion under cutting loads and to perform precise multi-axis interpolation.

After the mechanical structure was established, the chapter moved on to the electrical integration of the prototype. A centralized control cabinet was designed to organize the distribution of power and signals throughout the machine. High-voltage mains supply was routed through the protection and switching elements before feeding the dedicated DC power supplies, which in turn energized the stepper drivers and the spindle drive system. In parallel, the low-voltage control circuit was built around the ST-V3 motion controller, with the drive signals wired using a common-anode configuration and the homing sensors and safety devices integrated into the control architecture. This organization helped create a compact, functional, and reasonably noise-resistant electrical system.

The software stage completed the implementation process by linking the machine hardware to the control logic required for operation. Mach3 configuration, axis tuning, homing setup, and post-processing adaptation were all necessary to transform the assembled prototype into a usable CNC system. Overall, this chapter established the full physical and digital foundation of the machine, preparing it for future calibration, testing, and validation.

General Conclusion

This thesis presented the design, fabrication, and implementation of a compact 5-axis CNC milling machine prototype intended for educational and small-scale manufacturing applications. The project was driven by the growing need for accessible machining solutions capable of producing complex geometries with greater flexibility, while remaining economically feasible in contexts where industrial 5-axis machines are often beyond reach. Within this framework, the study established a complete engineering process, moving from theoretical analysis to physical realization, and demonstrated how advanced CNC technology can be adapted to a low-cost prototype without losing its technical relevance or design rigor.

The first part of the work provided the conceptual and technical foundation required to define the prototype. By reviewing CNC principles, machine architectures, motion systems, drive technologies, sensing elements, spindle configurations, and software chains, it became possible to identify the requirements of the machine with greater clarity. This theoretical phase made it easier to select an architecture that balanced rigidity, precision, modularity, and cost. It also highlighted the importance of coordinating all machine subsystems, since the performance of a CNC system depends not only on individual components, but also on the way they interact as a whole.

The second part focused on the practical realization of the prototype. The mechanical assembly of the frame, the linear axes, the rotary head, and the worktable formed the physical basis of the machine, while the electrical integration of the motors, drivers, sensors, protection devices, cabinet layout, and spindle system transformed the structure into a complete mechatronic platform. In parallel, the configuration of the Mach3 control environment, the tuning of the axes, the definition of homing and soft limits, and the adaptation of the CAM post-processing chain ensured that the prototype could be operated as a functional CNC system. This stage confirmed that the success of such a machine depends not only on the choice of components but also on the quality of their integration, calibration, and synchronization.

Overall, the project achieved its main objective, which is the development of a functional 5-axis CNC prototype that demonstrates the feasibility of a compact, modular, and affordable advanced machining platform. Although the prototype remains limited by the natural constraints of a laboratory-scale implementation, it provides

a solid basis for future improvements in structural rigidity, motion precision, feedback integration, and control optimization. It also opens the way to further work on industrial adaptation, performance enhancement, and broader educational use. In this sense, the thesis contributes to the effort of making advanced manufacturing technologies more accessible to students, researchers, and small innovators.

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