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**MechEng**  
Mechanical Engineering  
INTEGRATION



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# DESIGN, BUILD AND EXPERIMENTALLY EVALUATE A SMALL CNC MACHINE FOR WOOD MACHINING FEATURING MACH3 CONTROLLER (PART 1).



BACHELOR THESIS Vietnamese-German University

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*November, 2022*

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## Disclaimer

This dissertation was submitted to the Mechanical Engineering Department at the Vietnamese-German University and the RUHR UNIVERSITÄT BOCHUM in order to fulfill the requirements for the Mechanical Engineering Bachelor's degree. This thesis project is entirely my own work and, except where otherwise indicated, describes my research.

Presenter and project owner

Doan Huu Binh Phuong



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## Abstract

CNC-based machines have been covering many applications in large-scale industrial enterprises. These machines, together with control systems, improve efficiency robustly. Simultaneously, smaller businesses such as hobbyists, semi-professionals, or even students wanted solutions for small-scale and portable CNC machines for their own purpose. This paper discusses the process of designing and developing a 3-axis CNC milling machine that is controlled by a personal computer and meets requirements for a small-scale and wide range of milling abilities. The machine is constructed on a vertical axis with a close-frame structure.

To generate a rigid body frame structure, aluminum extrusion profiles are used in the assembly process. The Mach3 software is the human-machine interface for this project. This machine design is improved in precision as the servo motor is totally a better choice against the stepper, therefore increasing efficiency and flexibility.

**Keywords: CNC-based, Milling machine, Servo motor, Small-scale, Mach 3.**



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# Chapter 1: Introduction

## 1.1 Problem statement

The technology known as CNC, or Computerized Numerical Control, is a technique that defines the coordinate system using computer-based software. In order to accomplish this method, the appropriate object is typically pulled into a CAD device for G-code translations into system coordinate commands. The process is widely used in manufacturing as milling, drilling, turning, etc. The constructions of the frame for CNC machines can be the same, the purpose is decided by components selection.

CNC milling is a machining process that utilizes rotating cutting tools to create shapes and lines on a stationary workpiece. As mentioned above, the milling machine is determined by the selection of milling ends, but it can be a drilling machine as I change into drilling ends.

According to Piotr Boral's 2019 research, a lot of semi-professional CNC machines have recently been built widely and offered as commercial goods [1]. Small-scale and portable are the aims of these products. The current trend increases the familiarity with the CNC machines as well as encourages engineers to develop, customize and improve the design of the machines, which in turn create designs with multiple functions or compact machines specified for one purpose only.

However, these commercial models at the moment use the same components which will limit their abilities. The stepper motors in these builds have characteristics that are overwhelmed by those of the servo motors. As a result, the servo motor is chosen to accompany us in this design. The prototype can have the characteristic of commercial goods as it is not too big, affordable, and compact but also carries the abilities of a medium CNC build for factories. This machine can be developed further to enable the ability to work automatically as the servo pack can be controlled by a programmable logic circuit, which will help in mass production.

Any design project has a wide range of requirements which are often set by various project stakeholders. The more detailed technical needs will be covered in the following section. The requirements for this particular thesis are categorized into the list below.

- 1) The machine must be moveable, dimensions no more than 60x60x60cm. This makes it easier to fit it on a workstation or tabletop.

- 2) Any sort of wood fiber, particle, or strand material bonded together with an adhesive or binding chemical is referred to as engineered wood, or composite wood.

3) As long as the majority of tasks are finished within a day, the feed rates—the rates at which the cutting tool is moving—will be calculated and adjusted with the maximum cutting speeds at 1500 RPM. It is necessary to set a maximum rate where the milling operation would require coolant because it would complicate the machine too many.

4) The machine should be able to handle a 20x20x20cm workpiece. This requirement allows students to fabricate the majority of the parts they want. The machine should, as a minimum, have one axis that is unhindered, enabling the production of parts that are longer in one dimension.

5) Applying Mach 3 CNC control software, which is regarded as the most user-friendly and trustable — from DIY projects to industrial machining.

6) The machine should operate using the geometric code (G-code) CNC programming language, which instructs the CNC machine what kind of action to carry out.

7) The machine's microcontroller is an AKZ250, and its three main axes are controlled by servo packs and a DC motor.

## 1.2 Objectives



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The project aims to design and construct a prototype of a CNC milling machine that is controlled by a personal computer that runs MACH3 software. The machine will use AKZ250 as the microcontroller, with 3 servo packs for 3 main axes and a DC motor for the spindle. This machine's current goal is to function as a g-code command from the PC with high precision and acceptable speed.

## 1.3 Scope of implementation

- Content 1: Design, construction, and assembly of the frame.
- Content 2: Design, construction, and assembly of the transmission mechanism.
- Content 3: Communication between PC and AKZ250/ Servo pack and AKZ250.
- Content 4: Review, evaluate the result of the implementation, and finish the model.
- Content 5: Sample testing the machine.
- Content 6: Finish the thesis.

## 1.4 Outline

### Chapter 1: Introduction

- The issue and the reason why choosing the topics.
- Objective, research content, limitations, and project layout.

### Chapter 2: Background study



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- Background study is used to solve the problem.
- Hardware specifications for bought parts
- Software introduction.

### Chapter 3: Design of the CNC machine

- Hardware design for parts

### Chapter 4: Build of the CNC machine

- Bill of materials and machine specifications
- Wirings and programming

### Chapter 5: Machine Prototype

- Attempt on the first build of the machine.

### Chapter 6: Conclusions and future works

- Results of the project include the study period, results, comments, review of the project, and its practice.

## 1.5 Limitations

The project “Conceptual Design and Prototype Development of Simple Pendulum for experimental study of non-linear control method” focuses on the torque control process and the device's communication. These include:

The project “Design and Manufacturing of 3-axis CNC Milling Machine” focuses on the calculation for the physical system that can operate high-demand tasks on a small scale and is capable of accessible transportation. The design is limited to the following devices:

- A AKZ250 as the main controller.
- 3 Omron Servopack in associate with 3 axes
- 24V DC motor as the spindle .
- 24V Switching-mode power supply as the converter and supplier for all the system.
- Aluminum base products as frames and plates
- 3D printed plates
- Vit-me transmission
- Limit switches and metal detector sensor





## **Chapter 2. Background study and dimension decision.**

### **2.1 Numerical control system**

NC machine, short for Numerical control machine, is a typical comprise mechatronics product, which means it contains mechanical components driven by a numerical control system - an electrical component. The background, the basic components, the range of options, and the functions of NC systems, being the intelligence of NC machines, will all be covered in this part. You will gain a general awareness of CNC machines and a deep comprehension of the fundamentals of the NC system through the study in this area.

### **2.2 Introduction**

NC machine tools can be categorized as either "cutting" or "non-cutting" machines.

Cutting means the machine will process removing parts of the workpiece to finalize the finished piece. Milling machines and Turning machines are the most familiar examples among us. Non-cutting machines are to be used more in the industrial zone than in household or small-scale production as it changes the shape of the workpiece using force and is commonly used for single-use; pressing machines are good examples for this group. Additionally, systems such as robots or arms for grabbing, welding, and painting can be considered non-cutting NC machines.

The development of NC machines was intended to make it possible to process intricately shaped objects with high levels of precision. This led to the numerical controller only being used with milling machines. However, using NC for other machines has become increasingly popular as it enhances the production process and initializes conventional production.

The Figure 2.1 represents a simplified representation of the architecture of a machine controlled by an NC control system.

The task might be categorized as:

Offline tasks: CAD, CAPP, CAM

Online tasks: NC monitoring, machining, and measuring

Post-line tasks: Post-operation, Computer-aided inspection

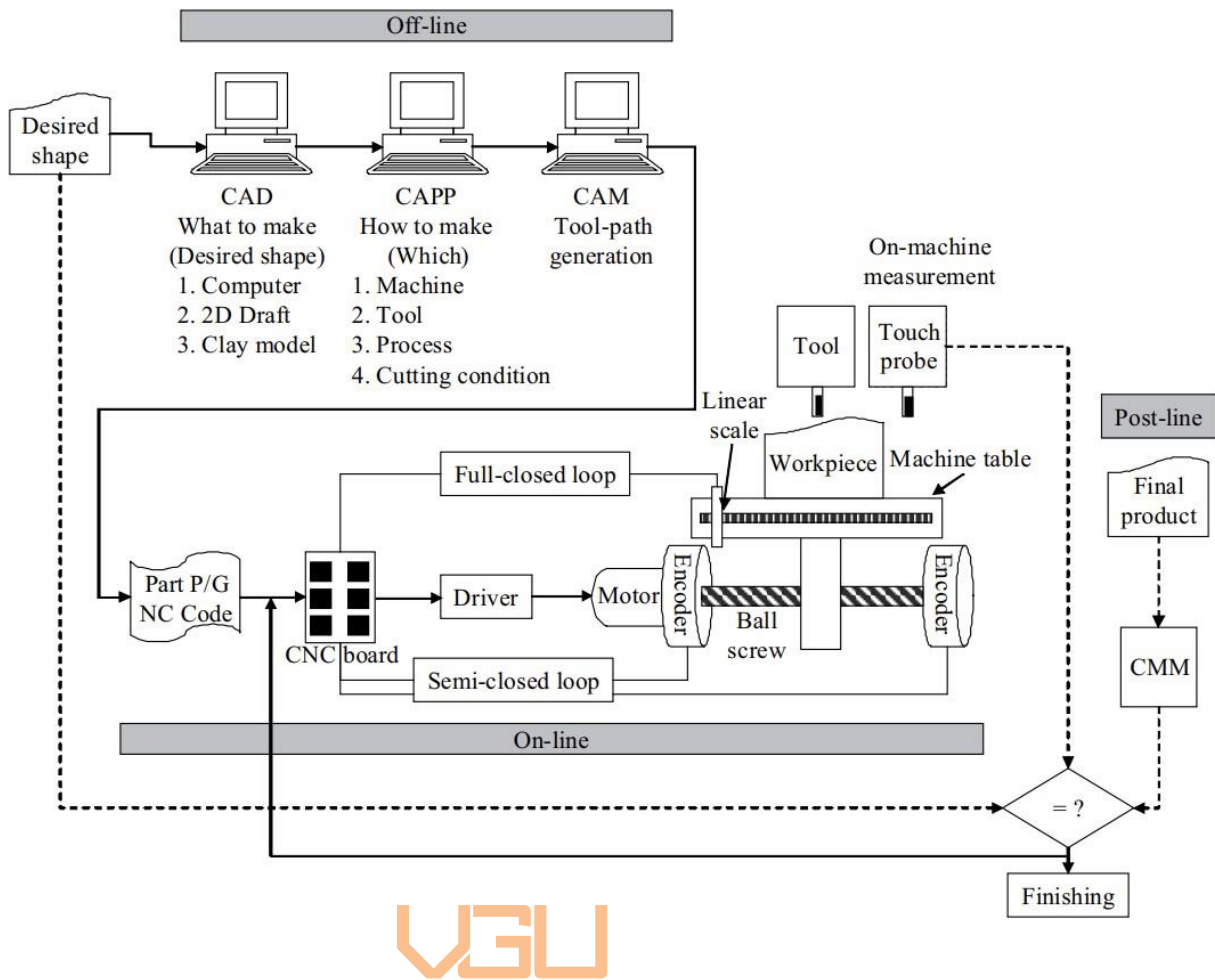


Figure 2.1: The Architecture of a CNC machine tools and machining operation flow

### 2.3 The components of the CNC machine

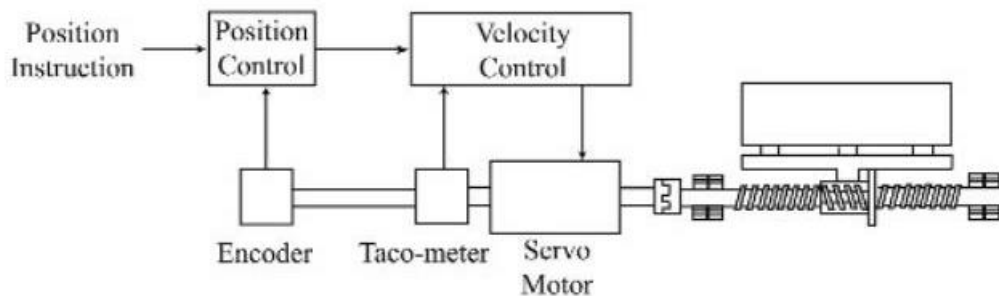


Figure 2.2: Primary CNC machine units

The three main components of a primary CNC machine are depicted in the pictures above: the NC unit, which functions as the Human-Machine Interface and computes information, the motor unit, and the driver unit. The NC unit itself is referred to as the CNC system. Position control is the CNC system's final function, and its output is supplied as a logical flow to the driver of the motor drive

system. The driver will control the torque and velocity of the servo motor, and the servo motor will move the workpiece as desired with the assistance of the transmission devices.

## **The NC unit**

The NC unit will continuously send an output signal instructing the driver during machine operation, so I call it a loop. Control loops are classified into feedback control loops and non-feedback control loops, also known as closed loops and open loops.

- **Open-loop**

Because open-loop control lacks feedback, it will be unable to adjust its movements. When the need for control accuracy is low, open-loop can be used, and as will be explained in step, this control mode requires a stepper motor.

An open-loop system has the simplest structure of all control methods because it does not require sensors or additional transmission for feedback signals. As previously stated, the driver will be driving a system with step impulses, so the system's accuracy is influenced by the stepper motor and the transmission protocol.



- **Closed loop**

As previously stated, a closed loop system has a constant feedback signal that allows the system to compare the desired value to the actual value and process the incorrect value. The system will strive to eliminate these faults in various ways, the most prevalent of which is the PID control approach in CNC systems.

I frequently hear about semi-closed and hybrid loops when discussing closed-loop control systems.

- **Semi-closed loop**

The semi-closed loop is still a closed loop, but the feedback signal is different. The feedback signal for a closed loop for a given control, such as position control, must also be position feedback. On the other hand, a semi-closed loop's feedback signal can be anything that can be converted to position using related formulas. As a result, the semiclosed loop has become the most often used control mechanism. For instance, a servo motor's shaft is equipped with a position detector that detects the rotational angle. The precision of the ball screw in the linear plan is substantially influenced by the position accuracy of the axis based on rotation angle feedback. By converting rotational movement to linear movement, I improve the precision of the ball screws and effectively solve the accuracy

problem. If necessary, Pitch error and backlash adjustment can be employed in NC to improve positional accuracy. The pitch-error compensation method declares that the accumulation of positional error at a certain pitch can be removed using changed servo driving instructions. The backlash compensation technique further asserts that extra pulses are sent to the servo drive system at each change in movement direction that corresponds to the amount of backlash. Recently, there has been an increase in the adoption of Hi-Lead-type ball screws with a large pitch for high-speed machining.

- **Hybrid loop**

The hybrid loop combines the closed and semi-closed loop to optimize machine performance by adjusting for mistakes that the other loops cannot. The gain has to be decreased when, as in the case of a large machine, it is challenging to increase stiffness according to the weight of the moving element or minimize wasted motion in a closed loop. Performance in terms of positioning time and accuracy suffers when the gain is small. In this example, I have a closed loop that is based on a linear scale and a semi-closed loop that detects position from a motor shaft. Since the machine is not a part of the control system, high gain regulation in the semi-closed loop is possible. By taking into account errors that the semi-closed loop is unable to correct, the closed loop increases accuracy. Despite its low gain, the closed loop is well-behaved since it simply compensates for positional inaccuracy. In an underperforming machine, combining the closed and semi-closed loops yields excellent accuracy and gain.

- **Kinds of controls in a system**

Each axis' three parameters will have its own independent loop in any feedback control system. The position is controlled by the most preferred loop and the outermost loop. This loop is often housed within the NC unit; the default settings of any device are for this control loop. The velocity control loop is in the middle, and the current control loop is on the inside; both are in a servo drive device. However, this is not the standard setting, and the locations can vary based on the designer's purpose

The feedback loop is optional for the machine's spindle. However, the velocity feedback control can be used to maintain a constant rotating speed. Because I am using a DC motor for the spindle in this project, the feedback mechanism cannot be used. I shall try to integrate the use of an AC motor to increase the machine's performance.

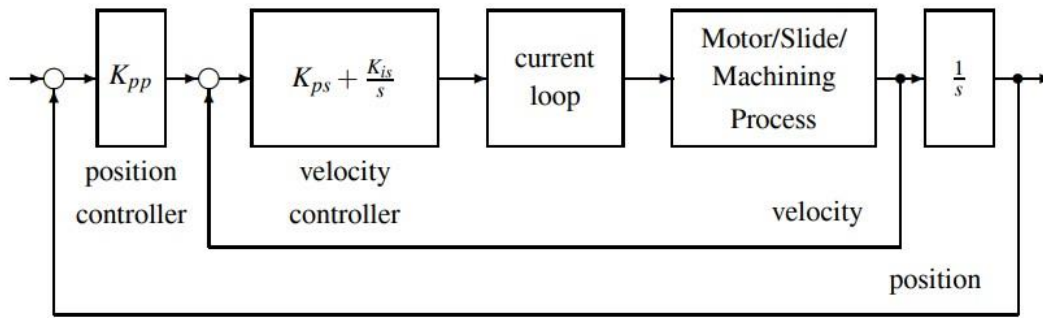


Figure 2.3: Three different types of CNC control loops

- **The Motor Unit**

The motor unit is the physical system that converts the NC unit's directives into machine movements. The two primary mechanisms of a CNC machine are depicted in the diagram below: a servo-driving mechanism and a spindle-driving mechanism. Permanent magnet synchronous motors have been used in CNC machine tools as servos to enhance performance. A servo motor and many different power transmission mechanisms are depicted as part of the servo driving system in the illustration. The servo will rotate as much as instructed by the NC unit to carry out the command. The connection will convey this rotation to the ball screw. The ball screw will convert this rotation into the linear movement of a nut, allowing the workpiece to move in a straight line. Based on the NC commands, the servo may regulate not only the position, but also the velocity and torque of the workpiece.

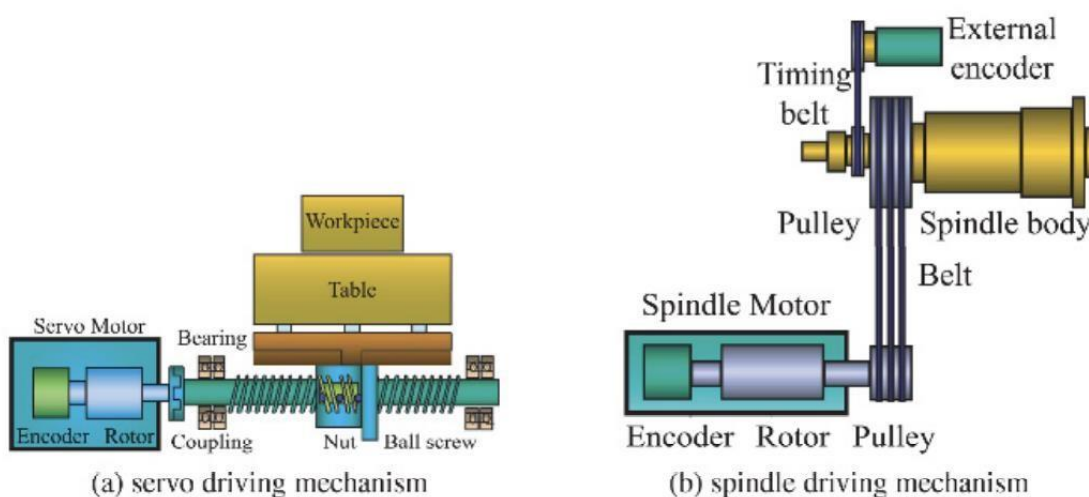


Figure 2.4: The Motor units

The spindle unit is seen in the second Figure, which comprises a spindle motor and a series of power transmission components. For large-scale machines, the spindle motor rotation will be conveyed to the spindle body via a belt and pulley system, with the velocity of the spindle body scaling up or down depending on the ratio of the two ends' pulley diameters. Instead of a belt, some machine tools employ gears to deliver power. Power transfer via gears, on the other hand, is unsuitable for high-speed milling. Recently a direct drive, in which the spindle motor and spindle body (headstock) are directly attached without a power transfer mechanism, has been employed for high-speed spinning exceeding 10,000 rpm. This technology could also be used for small-scale machines because it eliminates the need for extra torque calculations and reduces speed loss during transmission. The servo motor, which linearly drives the workpiece and the spindle, and the spindle motor, which powers the spindle, are referred to as "driving motors."

To be more specific, the spindle is the mechanism that creates enough cutting speed and torque by revolving at high speeds. As a result, high torque and high-speed restrictions are critical for spindle motors. Initially, DC motors were employed, but as industrial demand increased, more machines began to use induction motors due to their properties. It lacks a brush and outperforms DC motors in terms of size, weight, inertia, efficiency, maximum speed, and maintenance.

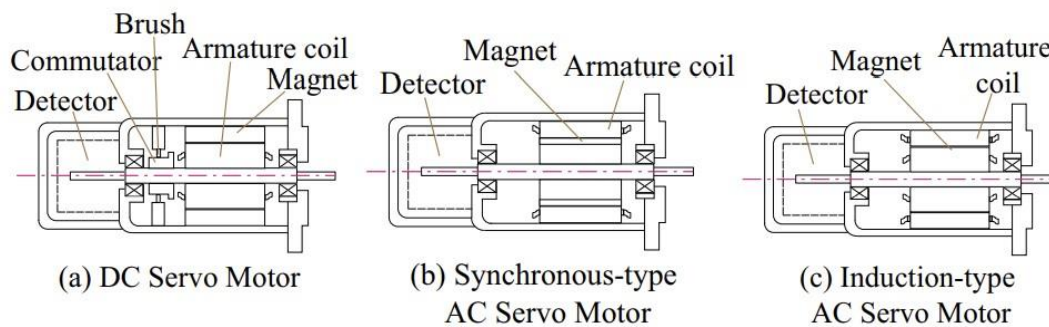
Strong torque, rapid acceleration, and quick reaction at low speed are necessary for the servo motor to regulate velocity and position simultaneously. Turning machines and machining centers, for example, will require high torque for heavy cutting at low speeds and high speed for quick movement at high speeds. Alternatively, motors with low inertia and high responsiveness are better suited to machines that often repeat jobs with a short machining time.

Machine tool servo motors must have a number of essential properties, including:

- The capacity to obtain an appropriate power production in accordance with workload.
- The capacity to respond promptly when given instructions.
- Reliable features for acceleration and deceleration
- Fairly broad velocity range.
- The capacity to safely control all ranges of velocity
- The capacity to run continuously for a lengthy time.
- The capacity to rapidly accelerate and decelerate.
- The capacity to provide enough torque when using a small block (have high-resolution range).

- It rotates easily also with high accuracy.
- The capacity to provide enough torque for stopping.
- High reliability and durability.

Easy maintenance Several servo-motor types developed to meet the aforementioned requirements are shown in the figure below: DC Servo Motor, Synchronous Type AC Servo Motor, and Induction Type AC Servo Motor are the three types of AC Servo Motors.



*Figure 2.5: Types of servo motor*  
  
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- **DC Servo Motor**

The DC Servo Motor is more sophisticated than the AC Servo Motor, as seen in the Figure. The stator, which is the stationary part of a DC servo motor and is made up of a cylindrical frame and a magnet, and the rotor, which is the rotating section and is made up of a shaft and brushes, are its two primary parts. The rotor core, which is made of metal and supports the armature, and the commutator are attached to the shaft, respectively. Current is supplied through the commutator by a brush made from the armature coil. A detector, which can be either an optic sensor or a tacho-generator, is installed into the rotor at the back of the shaft to measure rotation speed. The torque of a direct current servo motor is related to the amount of current supplied to the servo. As a result, a simple circuit can be used to create the controller for this type. The main factor limiting power production is heat generated inside the motor as a result of the action of the current. As a result, in order to achieve high torque, I must supply an efficient heat evacuation system. DC servo motors provide a wide velocity range and a low price. Friction with the brushes, on the other hand, causes mechanical loss and noise. Thus the brushes must be maintained.



- **Synchronous-type AC Servo Motor**

The magnet of the synchronous-type AC servo motor is coupled to the spinning section, as opposed to the DC servo motor, and the armature coil is looped around the inside of the stator. It's as if they trade places with each other. The armature coil's end links with a lead wire to obtain current from outside the stator. Because of this structural feature, there can be no attached brush inside the servo, hence the name "brushless servo motor." This arrangement also improves stator cooling by letting cooling occur directly from the outside, providing the servo some resistance to temperature growth.

Because of the rectification spark, there is no limit to the greatest velocity that a synchronous-type AC servo motor may achieve, resulting in an excellent torque characteristic in a high-speed environment.

Furthermore, because there is no brush, it can be used for an extended period of time without requiring maintenance. The sole difference between this sort of servo and a DC servo motor is that it uses an optical encoder as a detector of rotation velocity rather than a tachometer generator. A resolver is used instead of the AC servo motor.

The armature contribution in an AC Servo Motor is proportional to torque. As a result, stopping is simple, and a dynamic brake operates during an emergency stop. On the other hand, it employs a permanent magnet, which complicates the structure and necessitates the sensing of the rotor's position. High-frequency, primary torque ripple, and vibration source are all components of the armature provided current.

- **Induction-type AC Servo Motor**

An AC servo motor of the induction type has a construction that is relatively similar to an AC servo motor of the synchronous type. This particular sort of AC servo motor has a stator formed of a frame, a core, an armature coil, and lead wire, as opposed to a rotor composed of a shaft and a core made of conductors. For an induction-type AC servo motor, a relative position detector between the rotor and stator is not necessary. However, unlike a synchronous AC servo motor, the field current continues to flow even when the motor is turned off. As a result, dynamic braking is nearly impossible; also, heat loss is unavoidable.

The table below compares the advantages, shortcomings, and other features of the servo motors discussed.



	<b>DC Servo Motor</b>	<b>Synchronous Type AC Servo Motor</b>	<b>Induction Type AC Servo Motor</b>
<b>Strengths</b>	Low price Broad velocity range Easy control	Brushless Easy stop	Simple structure No detector needed
<b>Weaknesses</b>	Heat Brush worn Noise Position-detection needed	Complex structure Torque ripple Vibration Position-detection needed	Dynamic braking impossible Loss of heating
<b>Capacity</b>	Small	Small or medium	Medium or large
<b>Sensor</b>	Unnecessary	Encoder Resolver	Unnecessary
<b>Life length</b>	Depends on brush life	Depends on bearing life	Depends on bearing life
<b>High speed</b>	Inadequate	Applicable	Optimized
<b>Resistance</b>	Poor	Good	Good
<b>Permanent magnet</b>	Exists	Exists	None

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 Table 2.1: Servo-motor overview

- **Encoder**

An encoder is a device that is commonly included with servo motors to detect position changes for position control. Typically, it is incorporated directly into the shaft of the power transmission. I can also use the encoder to control other parameters connected to changes in an equation, such as velocity, torque, and so on. For example, the velocity of the servo can be represented by the generated pulses in a unit of time or the period between pulses. The encoder is classified based on its substance (magnetic or optical) and function (absolute or incremental). Because the function is affected by the Electrical encoder with fixed resolution inside the servo drive, the encoder coupled to the servo in this project is magnetic-type and either incremental or absolute.

## The Driver unit (Servo pack)

- **Servo drive**

An electrical amplifier known as a servo drive continually monitors the servomechanism's feedback signal and makes adjustments to produce the desired behavior. The command signal typically reflects the desired location, but it can also represent the required torque or velocity. The associated encoder transmits the actual motor status to the servo drive, which translates the signal to its resolution scale and compares it to the desired motor status.

In a real-world system, suitable setups allow the servo to run at a velocity that is roughly equivalent to the velocity signal processed by the servo drive. Several gain parameters, such as proportional gain or stiffness, derivative gain or damping, and feedback gain, can be modified in a performance tuning process to attain or linear the intended performance. Although many servo motors are packaged with a specific drive, many drives are now interoperable with a variety of motors. In industrial processes, servo drives can handle digital or analog signals; some can even manage both.

Digital drives perform better because they have microprocessors that allow them to examine feedback signals while regulating machinery. To control velocity, for example, the CPU examines the encoder's pulse stream to identify the current status of the parameters. The mechanism can then modify speed by adjusting the pulse or blips, finally providing a speed controller effect. The recurring activities performed by the microprocessor during operation allow the digital drive to swiftly self-adjust; this might be useful in circumstances when mechanisms must adapt to a variety of environments with minimal effort. One disadvantage of digital drives is their high energy consumption. However, this is easily remedied because many digital drives now have batteries to check battery life. A digital drive's feedback system is similar to an analog drive's, except that the digital drive uses a microprocessor with algorithms that can forecast system circumstances.

Analog drives use electrical impulses ranging from -10 to +10 volts or 4 to 20 milliamperes. These control signals can be manually modified using potentiometers or certain circumstances, bound with buttons in the configuration. Most analog drives interact with tach generator feedback signals to detect and produce a torque demand, which requests currently in the mechanism dependent on the feedback loop. Because of their capacity to stop, accelerate, and decelerate in both directions, servo drives are referred to as four-quadrant drives. Analog drives use less energy than digital drives and can sometimes outperform them in terms of performance.

- **Servo pack**

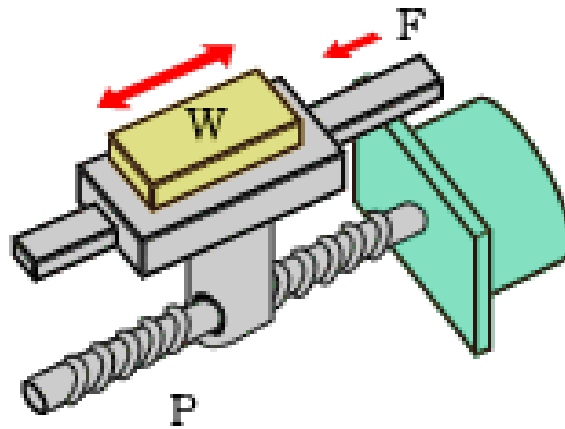
A servo pack consists of a drive and a compatible AC servo motor.



*Figure 2.6: A pack of servo driver and its compatible AC drive.*

## 2.4 Calculations and dimension decision

- Torque calculation.



*Figure 2.7: Force on the workpiece*

I first have the Torque that happen on the ball screw:

$$T = \frac{1}{2} \pi P (F + \mu W g) \quad (2.1)$$

Where:  $T$ : Torque (N-m)



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$F$ : External force (N)

$W$ : Mass of load (kg)

$\mu$ : Friction coefficient on sliding surface (Approx 0.05 to 0.2)

$g$ : Gravity acceleration ( $m/s^2$ )

$P$ : Ball screw lead length (m)

The force required to pull the mobile robot moving follows Newton's second law.

$$F_{load} = m \times a$$

(2.2)

Where:  $F_{load}$ : The force required (N)

$m$ : The mass of work piece (kg)

$a$ : Acceleration ( $m/s^2$ )

With  $m = 5kg$  and

$$a = 9,8m/s^2$$

$$\Rightarrow F_{load} = m \times a = 5 \times 9,8 = 49(N)$$

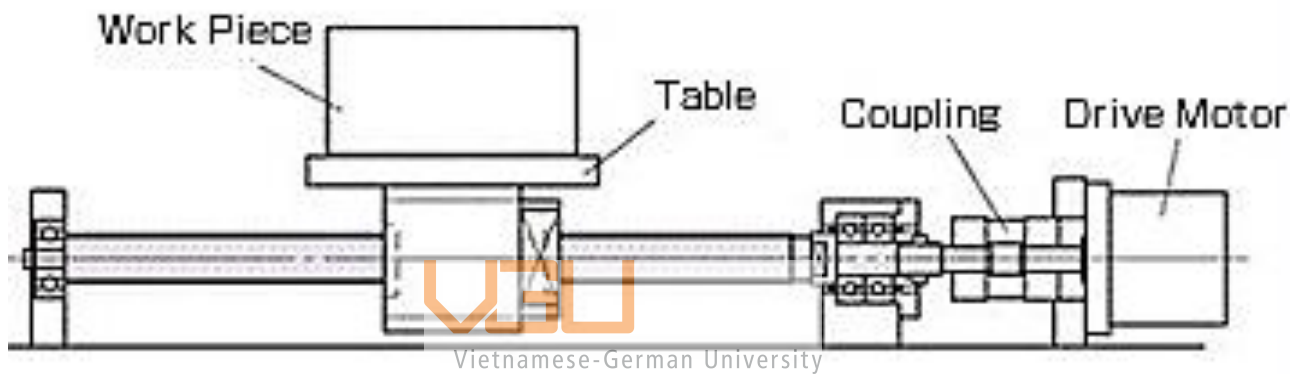
- The maximum load force is 49 N

Finally, the torque of machine is

$$T = \frac{1}{2\pi} P(F + \mu Wg) = \frac{1}{2\pi} 0,035(49 + 0,05 \times 5 \times 9,8) = 0,286(Nm)$$

- Must choose a motor with more torque than or equal to the theoretical torque.

- **Ball screw calculation**



*Figure 2.8: Calculation for ball screw*

Mass of work piece and table  $W = 5$  (kg)

Max Speed Required  $V_{max} = 1000$ (mm/s)

Duty Cycle Model Graph  $N_{max} = 3000$  ( $min^{-1}$ )

**(1) Lead Selection**

$$L \geq \frac{V_{max} \times 60}{N_{max}} = \frac{1000 \times 60}{3000} = 20(mm)$$

The length of lead must be more than 20mm. In my hardware, I use the lead with 35mm.

**(2) Nut Selection**

Axial Load Calculation

Acceleration  $\alpha = \frac{V_{max}}{t^3} = \frac{1000}{0,15} \times 10^{-3} = 6,67$  ( $m/s^2$ )

Constant Velocity Phase:

$$\text{Axial Load } (P_b) = \mu Wg = 0.02 \times 5 \times 9.8 = 0.98 \text{ (N)}$$

Acceleration Phase:

$$\text{Axial Load } (P_a) = W\alpha + \mu Wg = 5 \times 6.67 - 0.02 \times 5 \times 9.8 = 34.28 \text{ (N)}$$

Deceleration Phase:

$$\text{Axial Load } (P_c) = W\alpha - \mu Wg = 50 \times 6.67 - 0.02 \times 50 \times 9.8 = 32.42 \text{ (N)}$$

**Permissible speed**

$$n_c = \frac{60\lambda^2}{2\pi l_b^2} \sqrt{\frac{EI}{\rho A}} \text{ at } n_c : \text{critical speed (min}^{-1}\text{)}$$

*E*: Elastic modulus

*I*: Second moment of inertia ( $m^4$ )

$\rho$  : Density ( $kg/m^3$ )

*A*: Root cross-sectional area ( $m^2$ )

$\lambda = 3,927$  (for fixed-supported)

$l_b$  : Distance between mounting position ( $m$ )

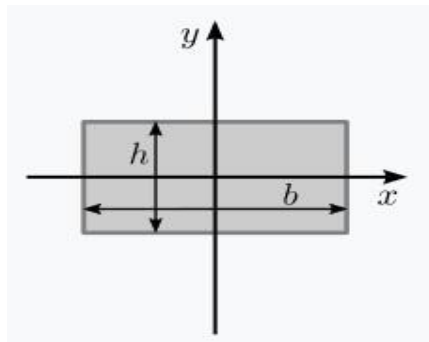
Material	Density $\rho$ ( $kg/m^3$ )	Young's Modulus $E$ ( $10^9 N/m^2$ )	Ultimate Strength $S_u$ ( $10^6 N/m^2$ )	Yield Strength $S_y$ ( $10^6 N/m^2$ )
Steel	7860	200	400	250
Aluminum	2710	70	110	90
Glass	2190	65	50	-
Concrete	2320	30	40	-
Wood	525	13	50	-
Bone	1900	9	170	-
Polystyrene	1050	3	48	-

*Table 2.2: Some materials' parameters*

My main material is wood so  $E= 13 \text{ Pa}$  and  $\rho =525(kg/m^3)$  and  $A$  depend on the size of the workpiece.

In addition, the second moment of inertia is a geometrical characteristic of an area that exhibits the distribution of its points with respect to any axis.

Therefore, a full rectangle with base dimension of  $b$  in width and  $h$  in height.



with  $h = 10 \text{ mm}$  and  $b = 15 \text{ mm}$

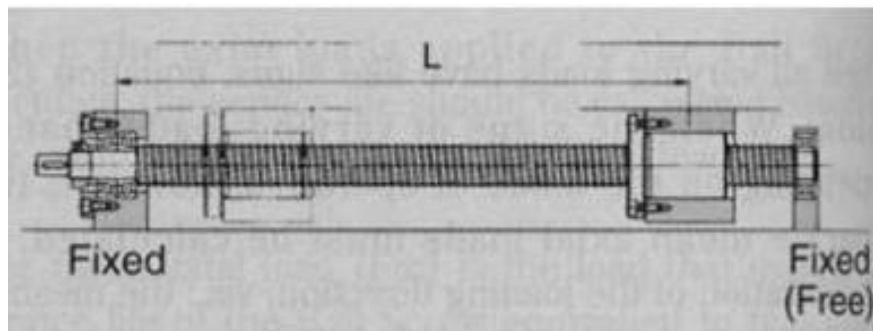
*Figure 2.9: A rectangular example*

$$I_x = \frac{bh^3}{12} = \frac{15 \cdot 10^3}{12} = 1250(\text{mm}^4) \text{ and } A = bh = 15 \cdot 10 = 150(\text{mm}^2)$$

$$\text{Finally, } n_c = \frac{60\lambda^2}{2\pi l_b^2} \sqrt{\frac{EI}{\rho A}} = \frac{60(3,927)^2}{2\pi(0,025)^2} \sqrt{\frac{13 \cdot 10^9 \cdot (0,125 \cdot 10^6)}{525 \cdot (0,15 \cdot 10^3)}} = 3,38 \cdot 10^{10} (\text{min}^{-1})$$

### (3) Axial rigidity of the shaft

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*Figure 2.10: The image of the fixed-supported shaft*

$$\text{Fixed-Supported } k_s = \frac{AE}{L} = \frac{(13 \cdot 10^9) \cdot (0,15 \cdot 10^3)}{0,0035} = 5,57 \cdot 10^{14} \text{ with } L = 35 \text{ mm (2.7)}$$

- **PWM DC motor control.**

There are lots of techniques to manage the speed of DC motors, but one extremely basic is to apply pulse width modulation (PWM). [5]

The benefit of utilizing pulse width modulation to control a tiny motor is that the power loss in the transistor is negligible since the switching transistor is either entirely "ON" or completely "OFF". As a result, the switching transistor dissipates far less power, enabling linear control that improves speed stability.

By constantly switching the power on and off, PWM (Pulse Width Modulation) is a technology that enables us to change the average value of the voltage. The average voltage is determined by the duty cycle, which is the ratio between the amount of time the signal is ON and OFF during a predetermined period. [6]

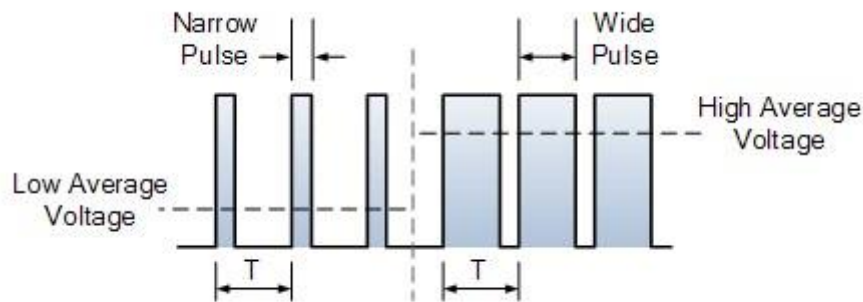


Figure 2.11: The average voltage of PWM

Without wasting any energy, *pulse width modulation* is an excellent technique for controlling the quantity of power delivered to a load. The aforementioned circuit may also be utilized to regulate the speed of a fan or to lessen the brightness of DC or LED lights. Pulse width modulation can be used to control it if you need to.

The duty Cycle is determined by:

$$DutyCycle = \frac{OnTime}{Period} 100\%$$

The average signal can be found as:

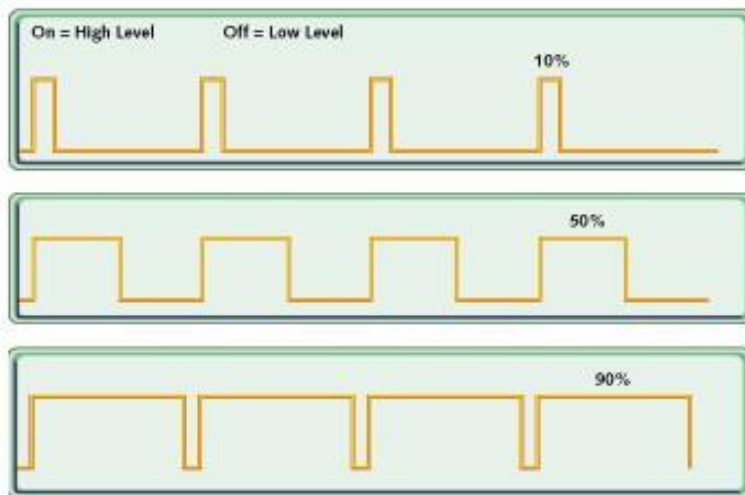
$$V_{avg} = \frac{1}{T} \int_0^{\tau} u(1)dt$$

$$V_{avg} = \frac{1}{T} u.t \Big|_0^{\tau}$$

$$V_{avg} = \frac{1}{T} u.\tau$$

$$V_{avg} = D.V_H + (1 - D).V_L$$





*Figure 2.12: The PWM signals with varying duty cycles.*

With an increasing Duty Cycle, a PWM signal's average value rises linearly.

In my project, I use a variable resistor to adjust PWM which helps me control the speed of the DC servo motor.

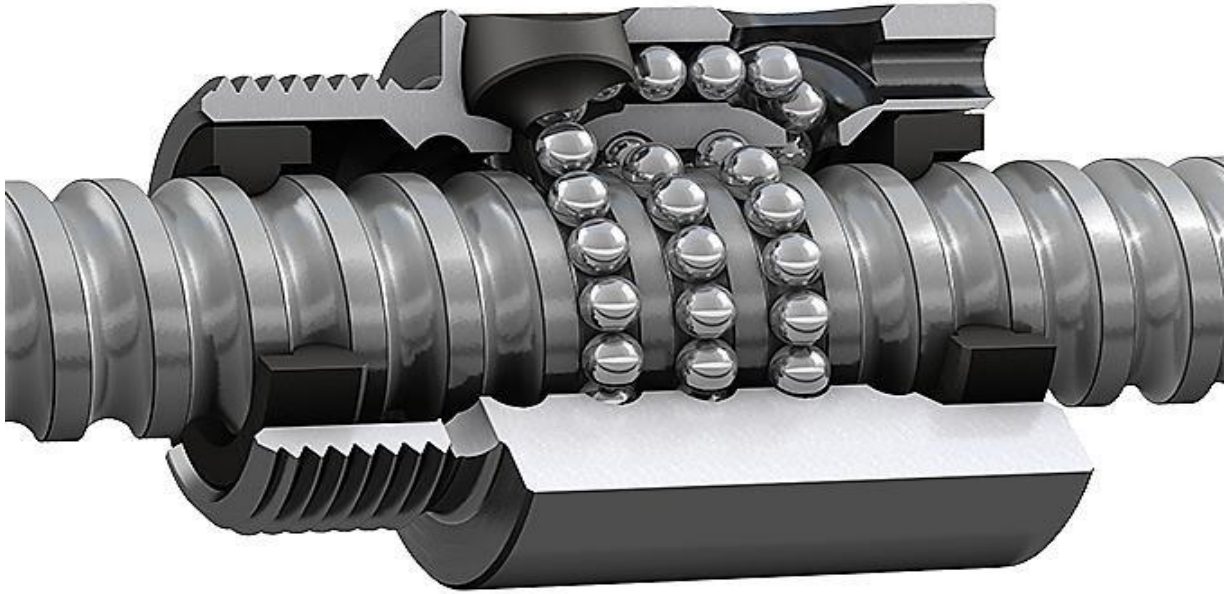
## 2.5 Hardware



### Linear movement

- **Ball screw**

A ball screw is, basically, a lead screw but is operated by a ball bearing; it is used to move the table or tools mounted on the tool's axis and changes the rotation motion from the servo motor into linear movement. The ball screw is usually paired with two Linear Movement (LM) guides to increase the linear movement's accuracy, smoothness, and stability. All of them are settled in parallel in the same plane with the desired linear movements and use the nut mechanism support. Inside the nut, there is a mechanism that allows the ball bearing to rotate continuously and move from one end to another. As these balls are in contact with the nut and the screw, the rotation applies a rolling contact to the surface between metals, minimizing the starting friction force and sliding friction and smoothing the movement even at low speed. Additionally, it is possible to reduce backlash by using a customized larger ball or double nut since since the lead of the screw and the displacement unit of the nut are connected.



*Figure 2.13: Ball screw mechanism*

- **Coupling**

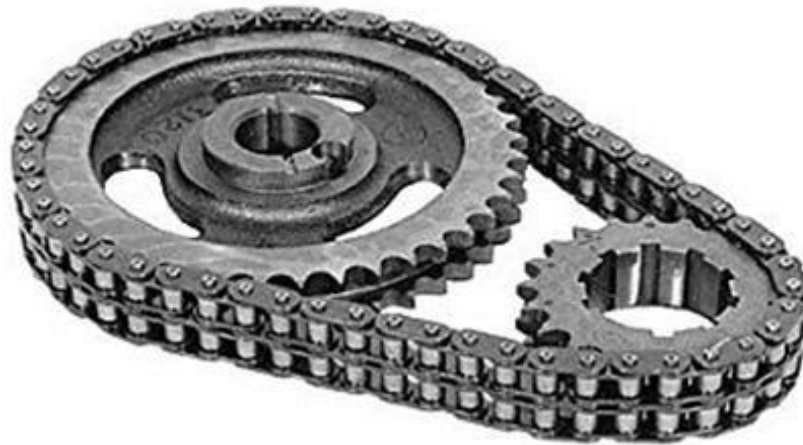
A coupling is a mechanical component that links the servo motor shaft to one end of the ball screw and transfers rotation from the servo to the ball screw. Another function of coupling in the system is to ensure that when the two shafts are joined, their centers are similar; however, this is not very practical in practice. To improve movement stability, the couplings should be insensitive to misalignment rotation centers. Flexible couplings, as illustrated in the figure below, have evenly spaced slots that allow them to bend at a little inclination in any direction.



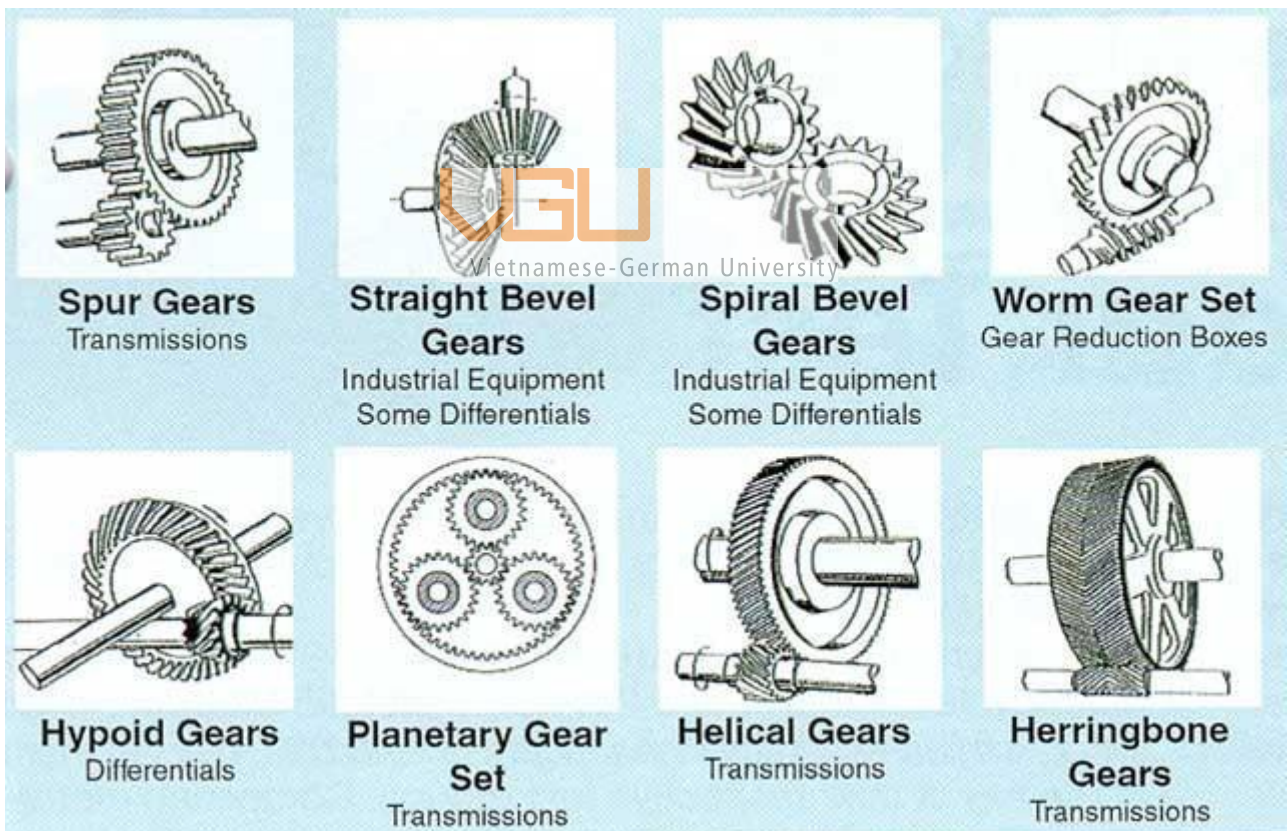
  
*Figure 2.14: 8\*8mm RS-flexible coupling D19 L25*  
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- **Belt and gears**

The belt and gear are mechanical components that carry rotational motion from the motors to the rotating body. They primarily serve to connect the spindle motor to the spindle body. Because these mechanical components do not connect the two-part sections directly, they are referred to as the "indirect driving method." the belt system is used to generate power by friction between the pulley and the belt. Gears are used as a transferring technique and speed reducer in systems requiring higher torque at a lower speed. A single or combination of mechanisms can exist in a single transmission system.



*Figure 2.15: A simple belt system*



*Figure 2.16: Type of gears*

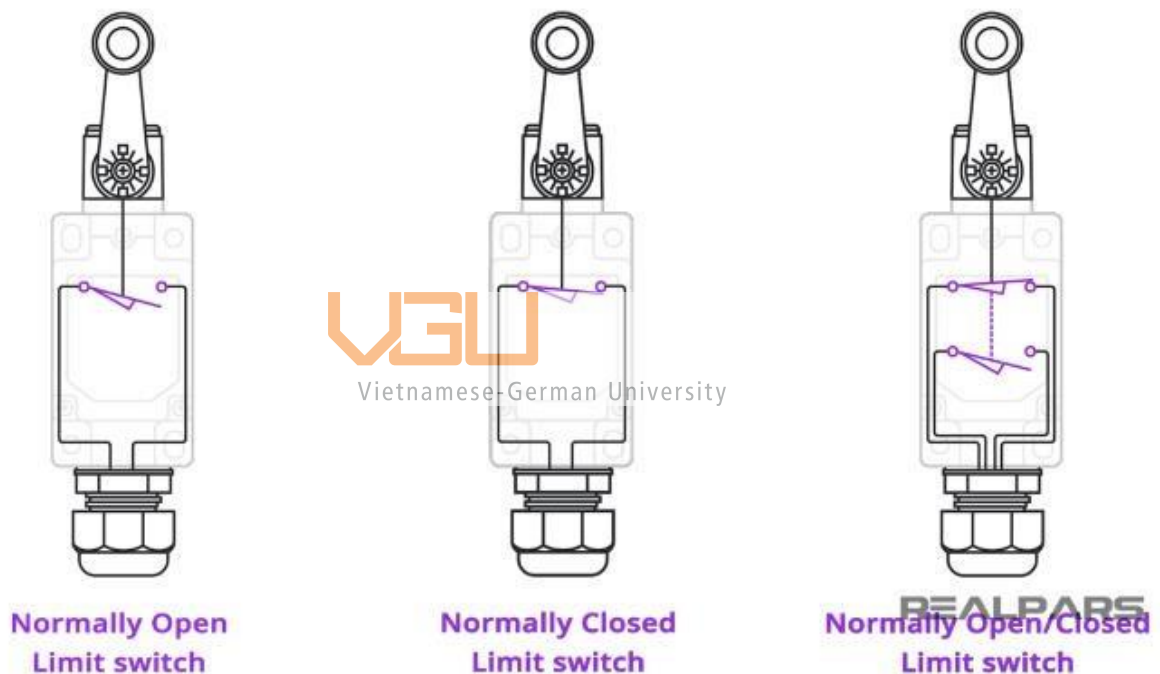
On the other hand, the indirect drive approach is unsuitable for high-speed milling, not to mention maintenance and noise. However, because the price is fair, it is a superior option sometimes.

The direct technique with coupling is recommended since there is no blowback and the amount of runout is minimal. Furthermore, it can suppress torque variation and is simple to use.

### Limit switches

The limit switch is an electromechanical switch that is mechanically connected to an electrical switch. The switch will operate based on the motion of a machine part or the presence of an object in touch with the actuator, causing an electrical connection to be made or broken.

They come in various configurations: NO stands for Normally Open, NC stands for Normally Closed, and combined, as indicated in the diagram below.



*Figure 2.17: Types of limit switches*

The name "limit" comes from the fact that they originally intended to indicate travel limits and an emergency stop. However, because of their ruggedness, dependability, and ease of installation, they are becoming available in various applications and situations.

Industrial control devices known as standardized limit switches have four different operator configurations: lever, roller plunger, whisker.

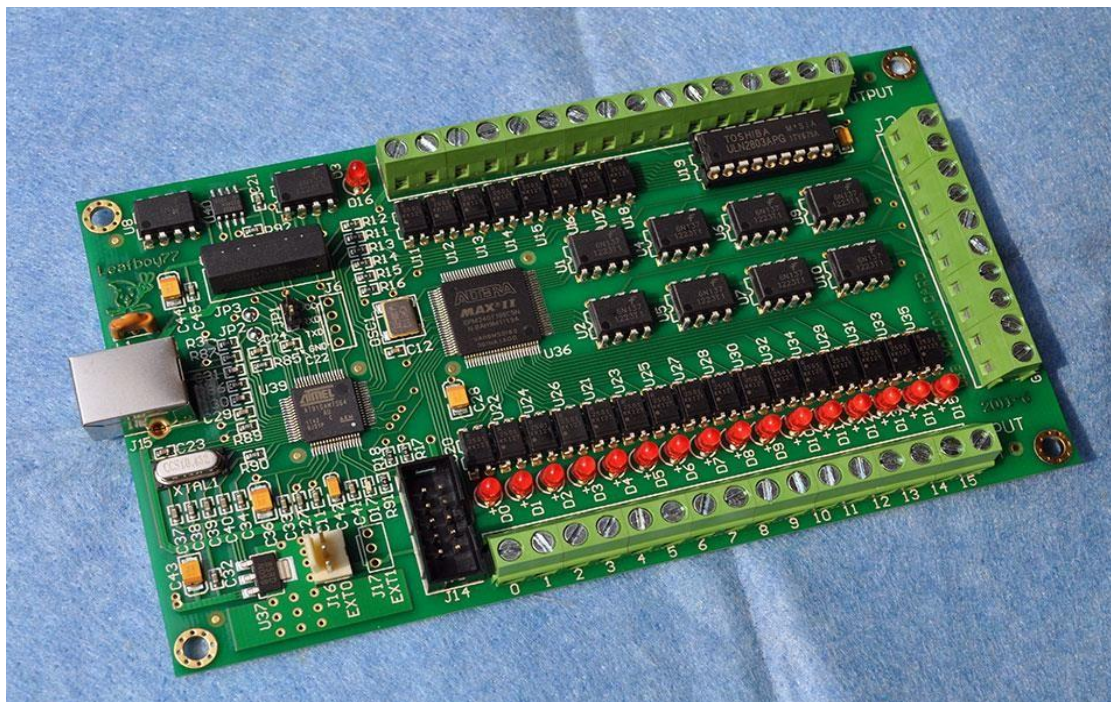


## Switching mode power supply

The switched-mode power supply is a high-efficiency (up to 90%) power converter that is compact and commonly utilized to power sensitive electronic equipment. It uses switching devices such as MOSFETs, capacitors, and inductors to turn on and off at high frequencies to stabilize the power provided to the system. They are classified depending on the input and output voltage types, with a voltage range ranging from 12V to 220V.

## Controller Akz250

The AKZ250 is a bespoke motion control main board built to completely support both Mach3 and Windows versions and play a role in software limiting and backlash. With sixteen general-purpose inputs and associated indicators, the board's architecture can handle up to sixteen limit switches or devices with the same functionalities. It has its independent power supply onboard, allowing it to run only via the USB connection; however, an additional power supply can be used to minimize the USB burden. This high-cost design, which includes ten 10MHz high-speed optocouplers and twenty-four general optocouplers for isolating all input/output signals, can deliver great performance and system stability. The output control instructions and input feedback signals use the same USB connection. However, they do not require USB drivers or even support for a USB hot-swapper because the card constantly monitors the USB connection status. Feed rate, spindle speed rate, and jog rate can all be adjusted using the attached adjustment knob and monitored using the Mach3 HMI.



*Figure 2.18: Controller AKZ250 board*

## 2.6 Software

### **Mach3**

Mach3 is ArtSoft's flagship product. There are two versions available: the Lockdown version, a stable, static release suggested for new users, and the Development version, which has up-to-date functionality as more patches are issued for this version. Because the code line limitation is the same for both versions without a license, I only need to use the Lockdown version for this project. Mach3 is a program that turns any computer into a CNC machine controller. It has many amazing features and is a terrific value for individuals needing a CNC control bundle. Mach3 operates on most Windows PCs by processing G-Code to control motor motion (stepper & servo). Because of its many advanced capabilities, such as being very customizable, is now the most intuitive CNC control software available. It has been utilized for many applications with various types of gear.

### **Inventor**

Inventor is an object-oriented system based on C++ and has a C application programmer's interface to create and render 3-D space. It was originally built on top of Iris GL and only work on specific workstations. Since GL only provides the low-level state machine while Inventor is a high-level descriptive graphics system for rendering 3-D graphics, it is a considerable upgrade, a life changer.



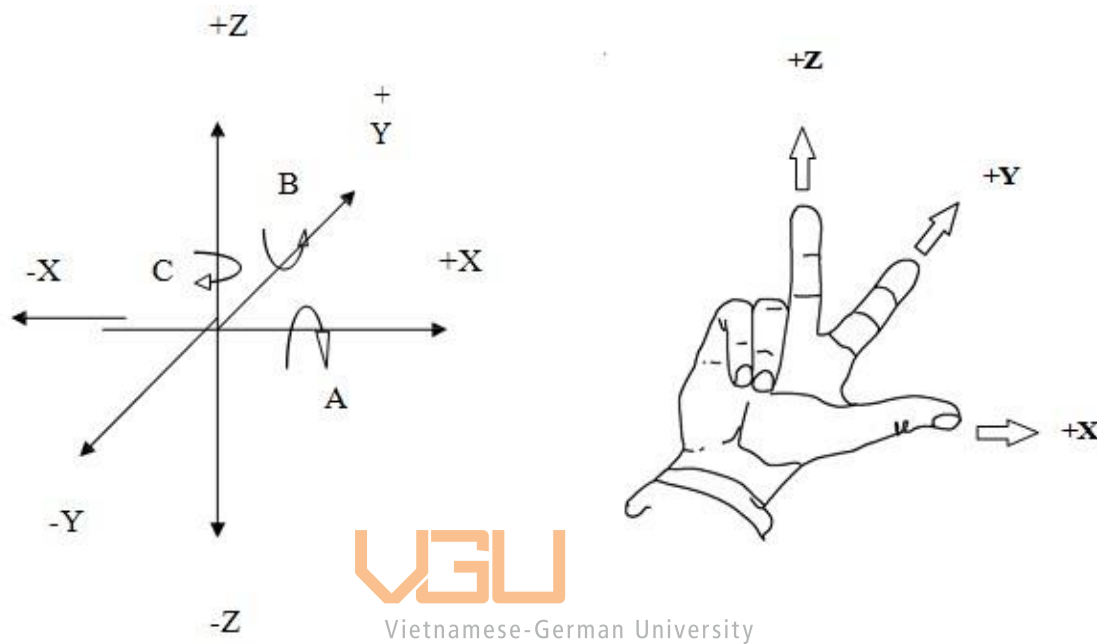
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The main focus of Inventor is to support interactive 3-D scenes, and it also supports animations and simulations. As the uses of CNC machines grow significantly among the fields, Inventor's creators release updates to support 3-D modeling to G-code and simulations of paths and release much better software to focus on this field as master CAM.

## Chapter 3: Design of the CNC machines

### 3.1 CNC Coordinates.

According to the ISO standard, cutting movements when machining details on CNC machines must be in a Descartes coordinate system according to the principle of the right hand. There are three forward movements according to the axes and three rotations in the corresponding axes.



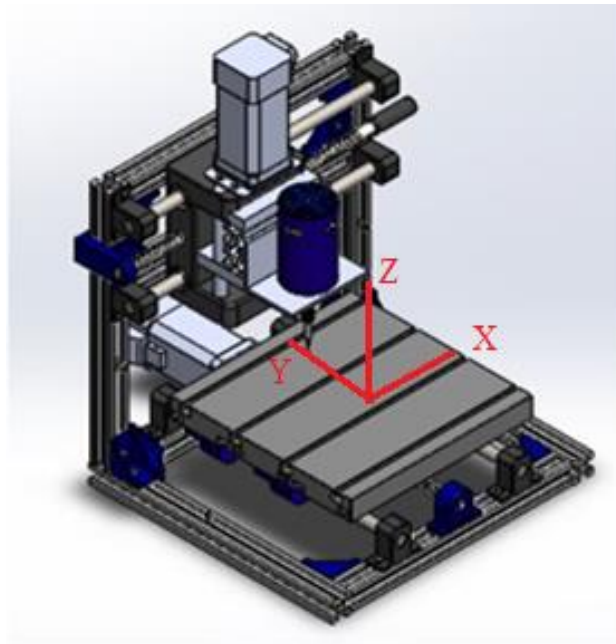
*Figure 3.1: The Descartes Coordinates*

The Z axis corresponds to the main axis of the CNC machine, and the positive direction is the dimension that increases the distance between the tool and the workpiece. The direction of rotation is positive along the clockwise direction (viewed from the origin of the coordinate).

The largest moving X-axis of the CNC machine is the most advanced. An example of a milling machine is a vertical knife movement, which is a horizontal knife movement. The positive direction is the dimension that increases the distance between the knife and the detail.

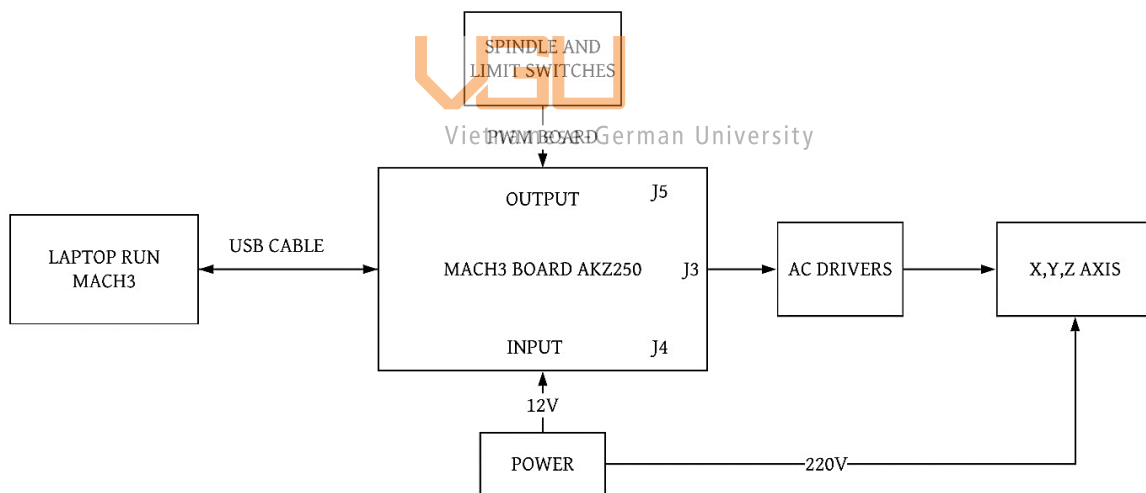
The Y axis is formed with two upper axes in the coordinate system. An example of a milling machine is the horizontal tool movement of the table on a lathe without this shaft.





*Figure 3.2: The coordination of a real CNC machine*

### 3.2 Block diagram.



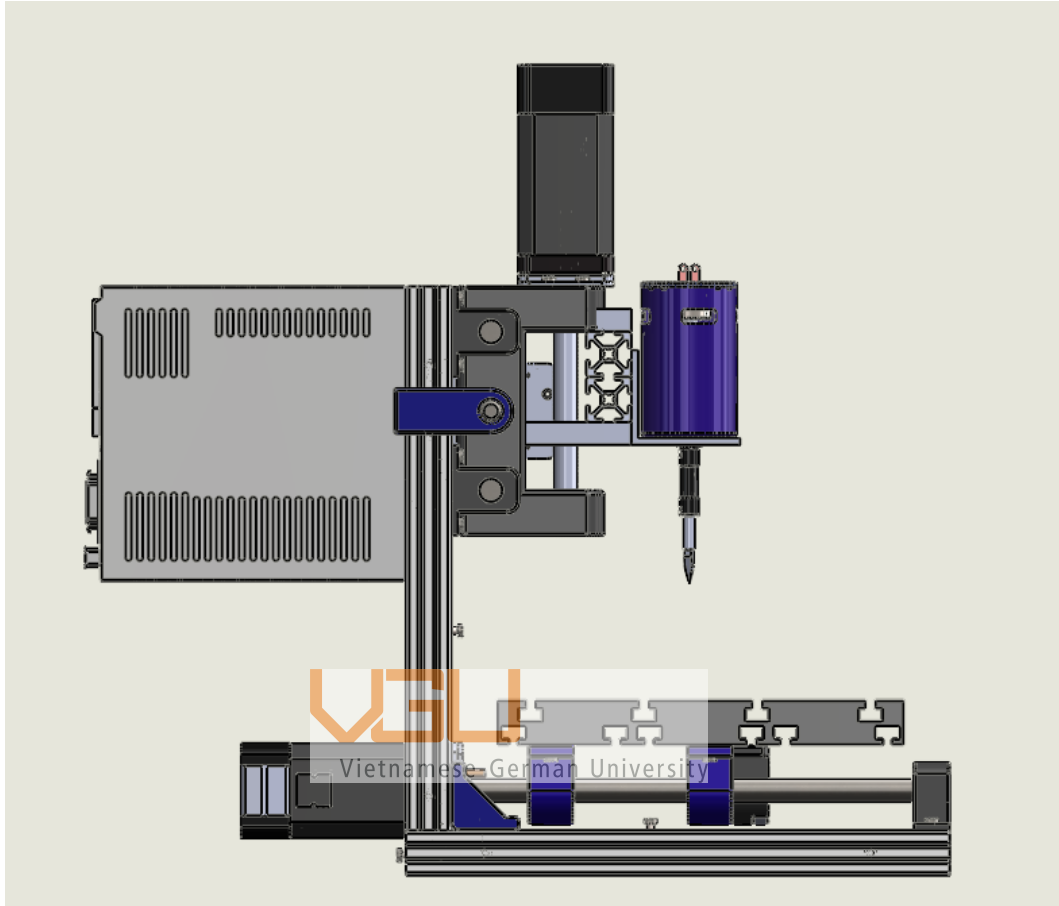
*Figure 3.3: Block diagram of CNC generally processing*

Mach3 software will process the design into G code and command the AKZ250 board through a USB cable. The AKZ250 will control the three servo motors by sending signals and receiving feedback from the servo drive. The current spindle in this project is the DC motor, so the signal command is just on and of from the PWM board. The power supply for the whole system is 220V household electric; one end will be connected to the PWM to supply a 24V voltage line for the AKZ250 board and the spindle, while the other will power the three servo drives directly with a 220V voltage line.

### 3.3 Designing hardware.

I first come up with the machine model using Solid Works 2018.

Designing CNC milling machine by Solid Works 2018 software.



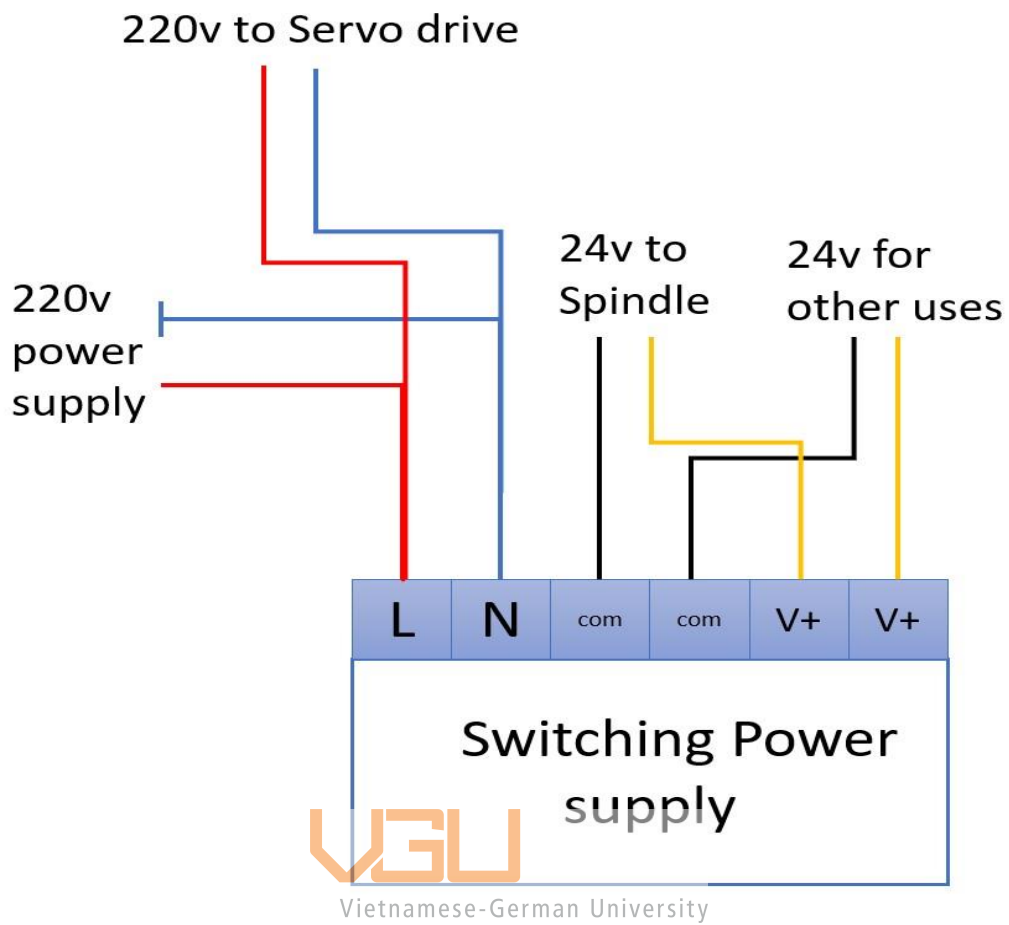
*Figure 3.4: The 2D drawing of the CNC milling machine*

I decide the dimension of the frame is 400 mm x 380mm x 360mm, lead to the dimension of the work piece that this machine can handle is around 400mm x 300mm 200mm. I also plan to have the Z axis adjustable so that it can handle higher work pieces.

### 3.4 Wirings

The switching power supply helps convert the standard household 220V AC into 24V DC that the spindle requires while simultaneously providing 220V for three Servo drives. The Servo drive built-in components will fulfil the Three-phase power supply that AC servo motors require. The controller, on the other hand, will fetch the power it need from the PC. In this project, I have selected the components that can optimize one power supply and are ready to go with just one plug.

### 3.5 Power



*Figure 3.5: Wiring for power source*



## Chapter 4: Build of the machine

### 4.1 Bill of materials

Item no.	Parts	Details	Quantities
1	Spindle	24VDC Motor	1
2	Servo drive	AC Servo driver R7D-BP01H	3
3	Servo motor	AC Servo motor R88M -G10030H	3
4	Limit switches	Short hinge roller lever LXW5-11G	6
5	Normal switches	Emergency Stop	1
6	Switching mode power supply	JiaJunS switching adaptor S-120-24	1
7	Controller	AKZ250	1
8	USB cable	1000mm type B	1
9	Motor cable	3000mm 4pin signal	3
10	Motor cable	3000mm 6pin power	3
11	Bakelite X axis front	240mm x 62mm mica	1
12	Bakelite X axis back	240mm x 67mm mica	1
13	Bakelite Load	240mm x 60mm mica	2
14	Bakelite Y axis	120mm x 100mm mica	2
15	Bakelite Y mount	60mm x 130mm mica	2
16	Bakelite Z axis	45mm x 90mm mica	2
17	Bakelite Z mount	65mm x 75mm stainless steel	2
18	Work plate	15180 x 300mm Aluminum profile	1
19	Lead screw X	T8 x400mm	1
20	Lead screw Y	T8 x 36mm	1
21	Lead screw Z	T8 x 180mm	1
22	Linear support rod X	Φ10 x 400mm	2
23	Linear support rod Y	Φ10 x 360mm	2
24	Linear support rod Z	Φ10 x 180mm	2
25	Ball screw	Φ8 x 36mm	3
26	Couplings	Φ10 x 32mm	3
27	L Plate	Support spindle 65mm x 65mm x 70mm	1

28	Aluminum Profile	2040V x 180mm	1
29	Aluminum Profile	2040V x 90mm	1
30	Aluminum Profile	2020V x 360mm	5
31	Aluminum Profile	2020V x 320mm	5
32	Aluminum Profile	2020V x 240mm	2
33	Bearing	10mm x 19mm x 29mm	12
34	Plates		4
35	Power supply	220V house hold cable	1
36	Hexagon socket screw	M5x8	60
37	T nut	M5	60
38	Hexagon socket screw	M3x14	12
39	Hexagon socket screw	M3x18	12
40	Hexagon socket screw	M5x10	12
41	Hexagon socket screw	M5x16	24

*Table 4.1: Bill of materials*

There are extra small parts to keep the machine nice and neat that are not included in the bill of materials



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## 4.2 Machine specifications

The Machine should be able to serve well as the specification below.

1	Full description	CNC milling machine
2	Number of axis	3
3	Servo Model	AC Servo motor R88M - G10030H AC Servo driver R7D - BP01H
4	Spindle Model	24VDC Motor
5	Controller Model	AKZ 250
6	Size	55cm x 50cm x 45cm
7	Weight	7kg
8	Power supply	220VAC – household
9	Work range	40cm x 30cm x 20cm
10	Spindle speed	1450-1650
11	Feed rate	50

12	Tool type	PCB CNC milling 3mm OEM
13	Maximum tool diameter	3mm
14	Emergency stop	Yes
15	Coolant type	None
16	Language	English

*Table 4.2: Machine specifications*

#### 4.2.1 AC servo motor

For feedback and closed-loop control, controllers are used with AC servomotors, which are AC motors with encoders built in. This allows for highly exact placement of these motors. Consequently, they may be strictly monitored to satisfy application requirements.

There are two categories into which AC servomotors are divided. These AC servo motors have two or three phases. Currently, two-phase squirrel cage induction motors are the most common form of AC servomotor. They are used for low power applications. Moreover, applications involving high power systems now make use of three-phase squirrel cage induction motors. [9]



*Figure 4.1: The AC Servo motor*

#### Advantages of AC servo:

When trying to rotate a motor that is under a strong load, the driver will increase the current going to the motor coil. In essence, there is no circumstance that is out of step.

Operation at high speeds is feasible.

#### The disadvantage of AC servo motor:

The motor speed control system is more complex and expensive than DC motor. Servo AC motor speed control system is based on frequency conversion. Motor speed is determined by the source frequency. One of the servo AC motor speed control methods is to convert the ac current into a DC

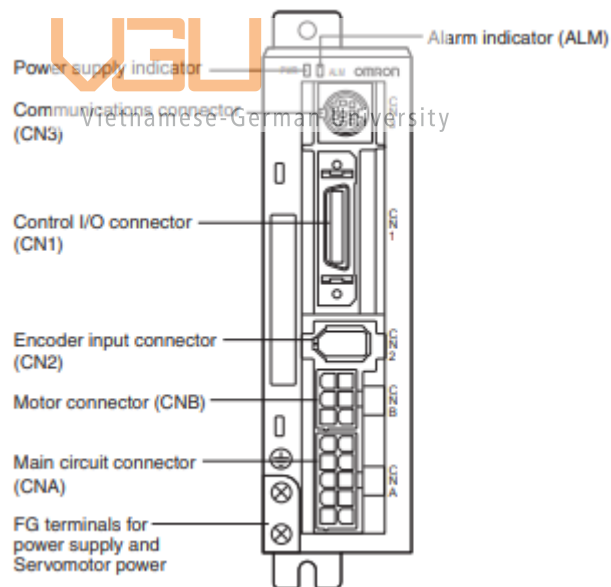
current using a three-phase rectifier, then convert the DC current to AC but at the selected frequency. Here, I use R88M-G10030H AC Servo Motor.



*Figure 4.2: The AC servo R88M-G10030H for real machine*

#### 4.2.2 Driver of AC Servo motor (R7D-BP01H)

When use driver R7D-BP01H that helps us connect between AC servo motor and hardware.



*Figure 4.3: Driver of AC servo motor [10]*

#### 4.2.3 DC Servo motor

Depending on whether they are mechanically commutated (with brushes and a commutator) or electronically commutated, DC motors are divided into brushed and brushless versions (via Hall sensors or other feedback). [11]



In addition, controlling the digital control machine tool axes requires precise control of both position and speed. Therefore, the DC motor must have a feedback circuit, the feedback signal is the motor shaft rotation speed or axis angle position. To ensure accurate table movement, the feedback signal must be continuously supplied. Here the feedback circuit of the used motor servo DC is encoder.



*Figure 4.4: DC servo motor*

**Performance Characteristics:**

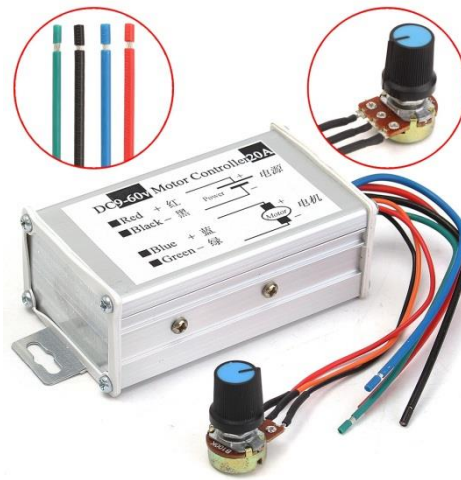
Continuous Torque	0.05 – 13 Nm
Peak Torque	0.14 – 42 Nm
Rated Speed	2000 – 3000 rpm
Input Supply Voltage	20.7 – 105 VDC
Motor Pole Count	4
Feedback Device	Encoder

*Table 4.3: The parameter of DC servo motor*

Color	Function
Red	DC5V
Black	GND
Red-Black	S-

*Table 4.4: Description of encoder wires for spindle motor*

### 4.3.3 DC Motor Speed Controller



*Figure 4.5: DC Motor Speed Controller*

#### Description:

- Input voltage: DC9-60V.
- Output voltage: Load Linear.
- Sustained current: 10A within.
- Maximum power: 600W.
- Speed mode: linear potentiometer.
- Speed range: PWM 0-100%.
- Operating frequency: 25KHZ

It can connect the motor with positive or negative, when the operating direction and expectations are inconsistent, you can adjust the line order to change direction.

## Chapter 5: Machine First prototype

### 5.1 The frame and the base

The frame is originally built as the initial design but I realized that it is too crowded to mount every thing on just 1 vertical plane. I came up with a new design that have 4 support profile and this build was much stronger than the initial one. It also provides more space to mount the drives and controllers.



*Figure 5.1: The Frame of the machine*



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*Figure 5.2: The build of X axis linear movement.*



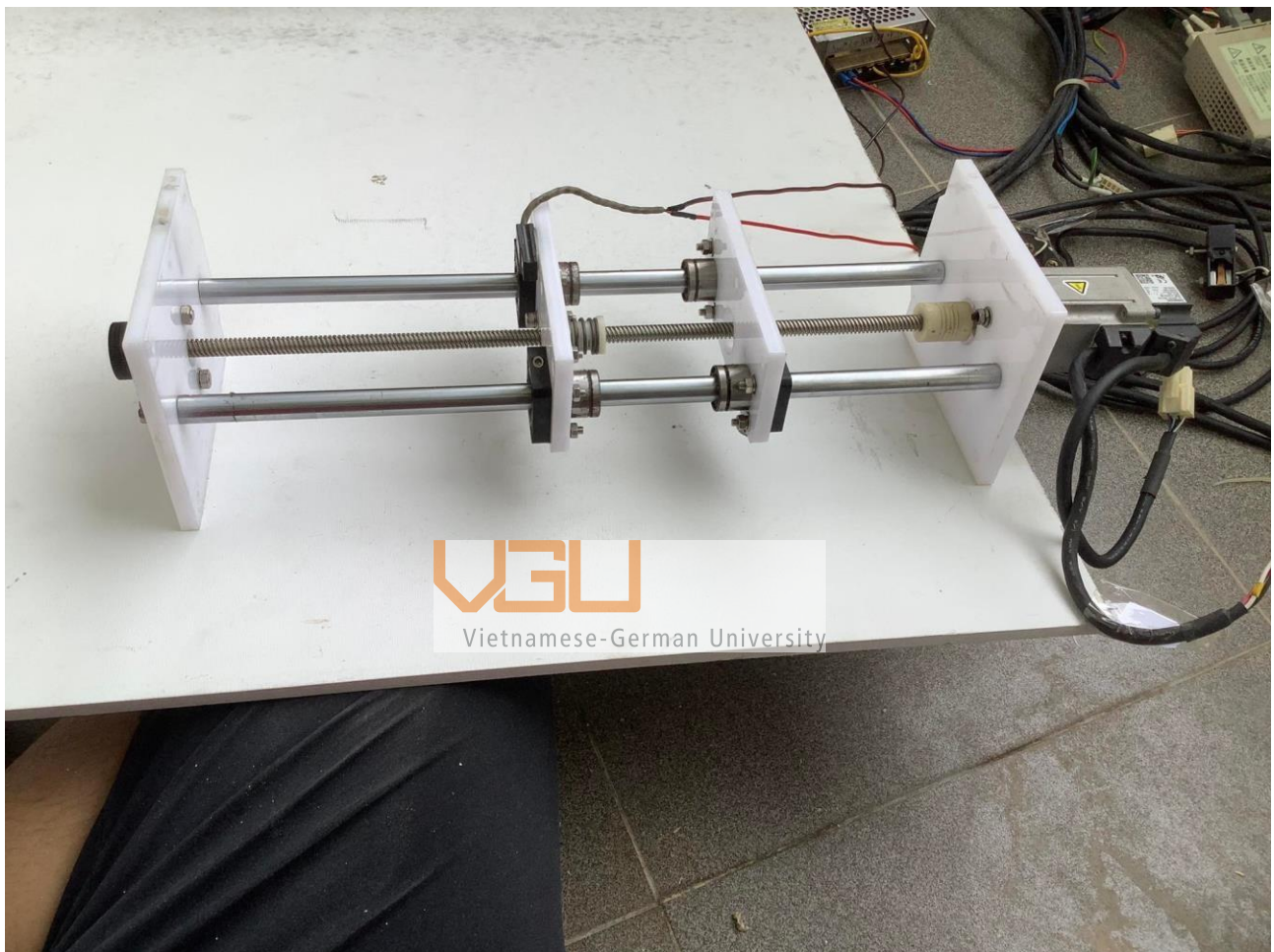


*Figure 5.3: The frame and the Base X axis.*

## 5.2 The Y-Z axis

### 5.2.1 Y axis linear movement

The Y axis will be carrying the Z axis but due to the earlier calculation and reasoning, I will have it built almost the same as the X axis. The mounting part, same as the work plate, will be attached on later.



*Figure 5.4: The Y axis.*

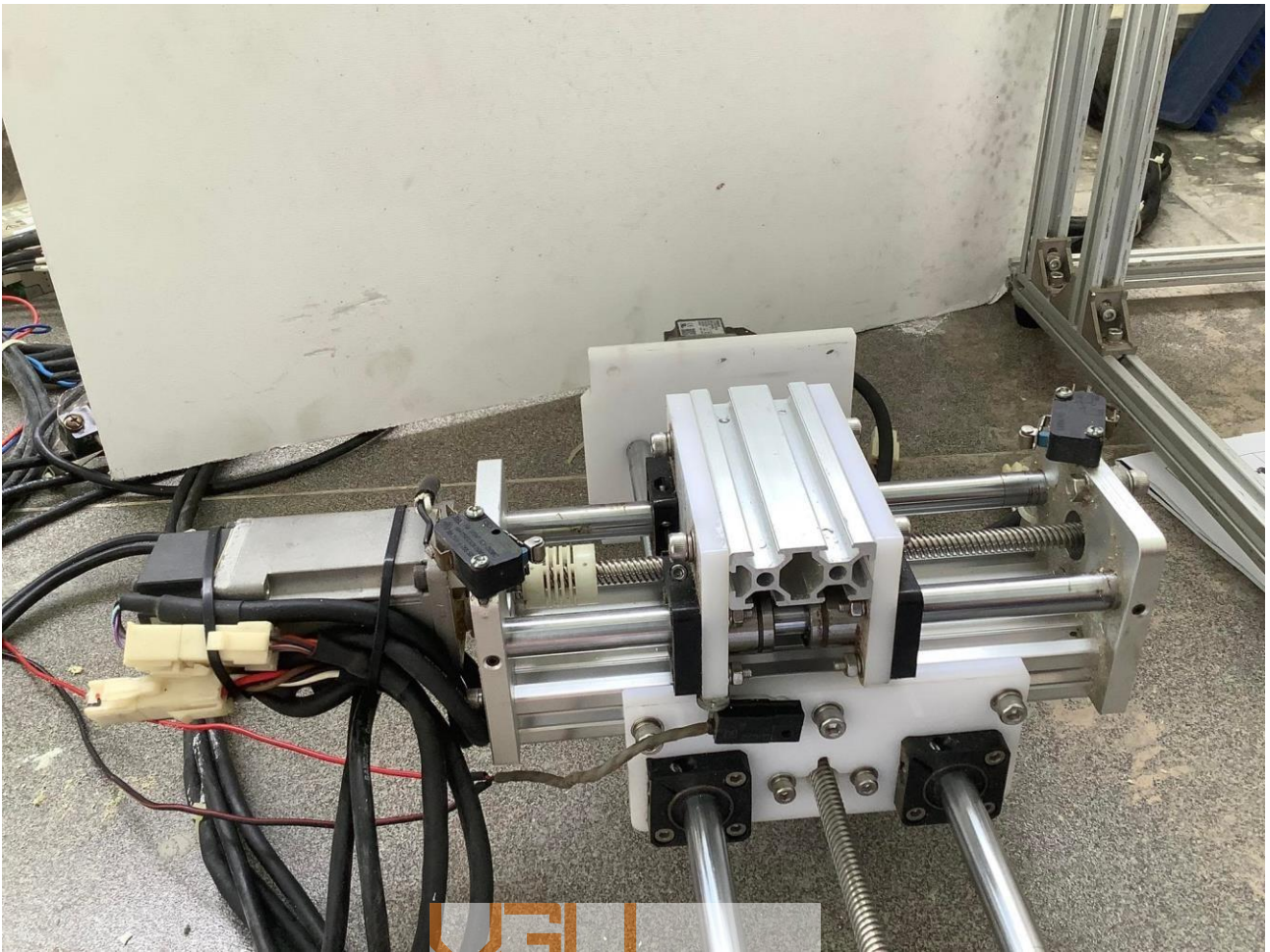
### 5.2.2 Z axis linear movement

The Z axis is the shortest axis among the three. It will have to carry the spindle. I have the L plate to support mounting the spindle.





*Figure 5.5: The Z axis with mount part for Y-Z connection.*

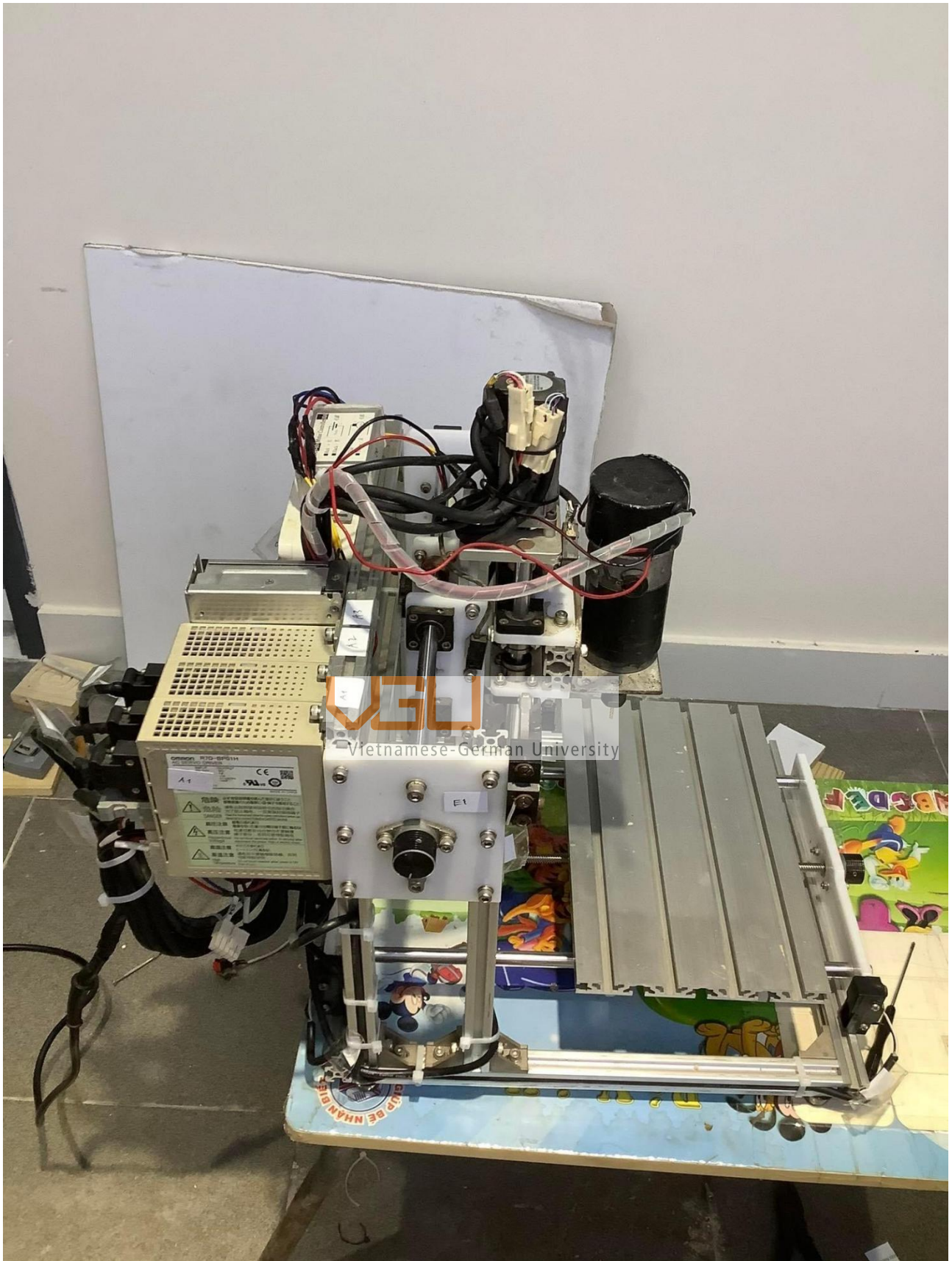


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*Figure 5.6: The connected Y-Z axis.*





*Figure 5.7: The machine with all axes mounted on.*



*Figure 5.8: The machine with all controllers mounted on.*



## **Chapter 6: Conclusion and future works**

### **6.1 Conclusion**

The final product is more stable than I initially thought. The machine can be carried around with one hand and operate much better than one prototype using the stepper motor I have at home. The weight, however, also increases a lot, but it still satisfies the criteria I set up at the beginning.

The limitation is that I cannot configure my servo drives and have to let them run by default, which is one of my only pain points during the working process.


### **6.2 Future works**

I aim to focus on the software that helps with generation G code for the 3d model to ensure the ability of my prototype. Further, I wanted to enhance the spindle by switching to an AC motor instead of a DC motor. Finding a way to config the servo drives is also one of my focuses. Configuring the drive will enable me to work in many driving modes and speeds.



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