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**DESIGN, BUILD AND EXPERIMENTALLY EVALUATE A SMALL CNC  
MACHINE FOR WOOD MACHINING FEATURING MACH3 CONTROLLER.  
PART 2: DETAILED DESIGN, FABRICATION AND EVALUATION**

Approved by

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Dr. Tran Trung Thanh, Second Supervisor



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Thesis Committee

## Disclaimer

This thesis is submitted to the Department of Mechanical Engineering, RUHR-UNIVERSITÄT BOCHUM and Vietnamese – German University in partial fulfillment of the requirement for the Bachelor's Degree in Mechanical Engineering. This thesis project is entirely our own work and, except where otherwise indicated, describes our research.

Presenter and project owner

Phan Ngoc Quang Huy



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Phan Ngoc Quang Huy



## Abstract

CNC-based machines have been used in many applications in large-scale industrial businesses. These machines, in conjunction with control systems, significantly improve efficiency. Simultaneously, smaller firms such as hobbyists, semi-professionals, and even students sought solutions for small-scale and portable CNC machines. This paper explains the process of designing and creating a 3-axis CNC milling machine operated by a personal computer and fits the needs of a small-scale and diverse range of milling capabilities. The machine is designed in a vertical position with a close frame structure. It is built with aluminum extrusion profiles to obtain a rigid body frame construction. The Mach3 software serves as the project's human-machine interface. This machine design is more precise since the servo motor is a far superior to the stepper motor, enhancing efficiency and versatility.

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



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# Table of Contents

Disclaimer.....	i
Acknowledgment.....	ii
Abstract.....	iii
Table of Contents.....	iv
List of Figures.....	vii
List of tables .....	viii
<b>Chapter 1: Introduction.....</b>	<b>1</b>
Problem statement.....	1
Objectives.....	2
Scope of implementation .....	2
Machine Specification .....	3
Outline .....	4
Limitations.....	5
<b>Chapter 2. Background study.....</b>	<b>6</b>
Numerical control system .....	6
Introduction.....	6
The components of the CNC machine.....	8
The NC unit.....	9
❖ Open-loop.....	9
❖ Closed loop .....	9
❖ Semi-closed loop .....	9
❖ Hybrid loop.....	10
Kinds of controls in a system.....	11
The Motor Unit.....	12
❖ DC Servo Motor .....	14
❖ Synchronous-type AC Servo Motor .....	15
❖ Induction-type AC Servo Motor.....	16
❖ Encoder.....	17
The Driver unit (Servo pack).....	18
❖ Servo drive.....	18
❖ Servo pack .....	19
Calculations .....	20
Milling speed and Feed forward calculation .....	20
Drilling speed and Feed downward calculation .....	20
Hardware.....	21
Linear movement .....	21

Ball screw.....	21
Coupling.....	22
Belt and gears.....	22
Limit switches.....	24
Switching mode power supply .....	24
Controller Akz250.....	25
Software .....	26
Mach3.....	26
Inkscape.....	26
<b>Chapter 3: Detail design of the CNC machines.....</b>	<b>27</b>
The Design and CAD model .....	27
The Frame and the base .....	28
Frame.....	28
The Y-Z axis.....	31
Y axis linear movement .....	31
Z axis linear movement .....	32
Spindle Mounting .....	34
<b>Chapter 4: Build of the machine .....</b>	<b>37</b>
Bill of materials and Machine specifications.....	37
Bill of materials.....	37
Machine specifications .....	38
Wirings.....	38
Power.....	38
Controllers .....	40
Programming .....	41
Mach3 setup.....	41
G-code .....	43
<b>Chapter 5: Experiments .....</b>	<b>47</b>
2D milling samples.....	47
The general CNC workflow .....	47
Vector graphics.....	50
Feed rate calculation .....	51
Locate Constrained Inscribed Circle .....	51
G01 – Linear Interpolation Accuracy .....	52
Maximum Inscribed.....	53
Minimum Inscribed.....	54
G02 and G03 – Circular Interpolation Accuracy .....	55

Maximum Inscribed.....	56
Minimum Inscribed.....	57
3D milling samples.....	58
<b>Chapter 6: Conclusion and future works .....</b>	<b>59</b>
Conclusion .....	59
Future works.....	59
<b>Appendix .....</b>	<b>60</b>
G code for Spiral sample.....	60
G code for Circle filling sample .....	63
<b>References.....</b>	<b>75</b>





# List of Figures

Figure 2.1: The Architecture of a NC machine tools and machining operation flow .....	7
Figure 2.2: Primary CNC machine units .....	8
Figure 2.3: Three kinds of control loop in CNC .....	11
Figure 2.4: The Motor units .....	12
Figure 2.5: Types of servo motor .....	14
Figure 2.6: A pack of servo driver and its compatible AC drive.....	19
Figure 2.7: Ball screw mechanism.....	21
Figure 2.8: 8*8mm RS-flexible coupling D19 L25 .....	22
Figure 2.9: A simple belt and gear system .....	23
Figure 2.10: Type of gears.....	23
Figure 2.11: Types of limit switches.....	24
Figure 2.12: Controller AKZ250 board .....	25
Figure 3.1 The 2D drawing of the CNC milling machine .....	27
Figure 3.2: The Frame of the machine .....	28
Figure 3.3: The build of X axis linear movement. ....	29
Figure 3.4: The frame and the Base X axis. ....	30
Figure 3.5: The Y axis.....	32
Figure 3.6: The Z axis with mount part for Y-Z connection. ....	33
Figure 3.7: The connected Y-Z axis. ....	34
Figure 3.8: The machine with all axes mounted on.....	35
Figure 3.9: The machine with all controller mounted on.....	36
Figure 4.1: The wiring of the whole machine .....	39
Figure 4.2: Wiring schema of the machine.....	40
Figure 4.3: Wiring for all component signals .....	40
Figure 4.4: The dialogue to choose motion card. ....	41
Figure 4.5: Ports and Pins configuration.....	42
Figure 4.6: Motor tuning and setup dialogue .....	42
Figure 4.7: Example of a G-code file .....	44
Figure 5.1: Sample Linear experiment .....	52
Figure 5.2: G01 - Linear Interpolation Accuracy checking Maximum Inscribed.....	53
Figure 5.3: G01 - Linear Interpolation Accuracy checking Minimum Inscribed .....	54
Figure 5.4: Sample of A clockwise G02 movement and G01 .....	55
Figure 5.5: G02 and G03 - Circular Interpolation Accuracy checking - Maximum Inscribed.....	56
Figure 5.6: G02 and G03 - Circular Interpolation Accuracy checking - Minimum Circumscribed .....	57

## List of tables

Table 2.1: Servo-motor summary .....	16
Table 4.1: Bill of materials.....	37
Table 4.2: Machine specifications.....	38
Table 4.3: Common G-codes.....	45
Table 4.4: Common M-codes.....	46
Table 5.: G01 - Linear Interpolation Accuracy checking Maximum Inscribed .....	53
Table 5: G01 - Linear Interpolation Accuracy checking Minimum Circumscribed .....	54
Table 5.: G02 and G03 - Circular Interpolation Accuracy checking - Maximum Inscribed .....	56
Table 5.: G02 and G03 - Circular Interpolation Accuracy checking - Minimum Circumscribed .....	57



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# Chapter 1: Introduction

## Problem statement

CNC machining describes any mechanical process controlled by a computer and defined by numbers. These numbers are usually coordinates, which means a CNC is essentially a big machine that plays connects the dots in three-dimensional space.

Technically, 3D printers and laser cutters are all in the same family. When people say CNC, they refer to CNC milling machines or other subtracted manufacturing tools like lathes. What makes CNC milling trickier than something like 3D printing is that it removes the materials to create shapes, not adding materials. Since the milling machine uses a sharp cutting tool at high speeds to rip material away, many things could go spectacularly wrong.

However, a massive amount of work must be done to achieve the final CNC-ed product using a milling machine. In this project, we focus on programming G-code and machining techniques that can proceed using the design from another project.



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## Objectives

In this project, I am aiming to design and manufacture a CNC mill based on a structural calculation and design of a simple CNC machine by Doan Huu Binh Phuong, my thesis partner. The intention is to build a mill from his pre-calculated data that could fit compactly on a tabletop in order to bring the CNC mill to a broad community. I hope that this mill will be used for custom parts and artisan projects instead of more expensive additive fabrication methods.

## 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.
- Content 4: Communication between Servo pack and AKZ250.
- Content 5: Review, evaluate the result of the implementation, and finish the model.
- Content 6: Sample testing the machine.
- Content 7: Finish the thesis.



## Machine Specification

There are various sets of requirements in any design project, which are frequently set by different stakeholders to the project. The more specific technological needs will be discussed in the following section. The criteria for this thesis are listed below:

1. The machine must be compact, with dimensions of 60x60x60cm. This allows it to simply fit on a table top or workbench.
2. Machineable materials can be used Engineered wood, also known as composite wood, refers to any sort of wood fiber, particle, or strand material that is kept together with the help of an adhesive or binding agent.
3. With maximum cutting speeds of 1500 RPM, feed rates (rates at which the cutting tool moves) are not critical and will be calculated and adjusted as long as most jobs are done within a day. As this would add unneeded intricacy to the machine, a maximum rate should be set where the milling operation would require coolant.
4. The machine should be capable of processing a workpiece of 20x20x20cm. This is a constraint that allows most of the parts that students require to be manufactured. As a minimum, the machine should have one clear axis, enabling for the production of parts that are longer in a single dimension.
5. Using Mach 3 CNC control software, which is acknowledged as the most user-friendly and dependable — from DIY projects to industrial milling.
6. The machine should be processed using a CNC programming language known as geometric code (G-code), which instructs the CNC machine what type of operation to do.
7. The machine will use AKZ250 as the microcontroller, with 3 servo packs for 3 main axes and a DC motor for the spindle.

Although this list is not detailed, it has the capability to define the design and provide insight in design decisions.

# Outline

## Chapter 1: Introduction

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

## Chapter 2: Background study

- 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



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## Chapter 4: Build of the CNC machine

- Bill of materials and machine specifications
- Wirings and programming

## Chapter 5: Experiments

- Results of sample test run with different objects.
- Accuracy of the samples

## Chapter 6: Conclusions and future works

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

## Limitations

"Design and Manufacturing of a 3-axis CNC Milling Machine" Based on the existing derived data, one can only consider static loading scenarios and ignore dynamic loads. This could be a mistake because mill vibrational modes are critical. This estimate, however, may be correct if the structure is stiff enough that static displacements are low. The following devices are excluded from the following devices:

- A AKZ250 as the main controller.
- 3 Omron Servo pack 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.**

### **Numerical control system**

*Numerical control* is a programmable automation in which numbers, letters, and symbols guide the process. In the case of machine tools, this programmable automation is employed to operate the machines. Often known as the NC, numerical control is widely employed in machine tools.

NC technology can be used for various tasks such as drafting, assembly, inspection, sheet metal working, etc. However, it is more commonly used for various metal machining techniques such as turning, drilling, milling, shaping, etc. Because of NC, all machining operations may be completed rapidly, resulting in much lower costs for bulk manufacture.

### **Introduction**

The work flow of a machine using an NC control system can be summarized as the Fig. 2.1

The task can be classified as:

Offline tasks: CAD, CAPP, CAM



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Online tasks: NC monitoring, machining and measuring

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



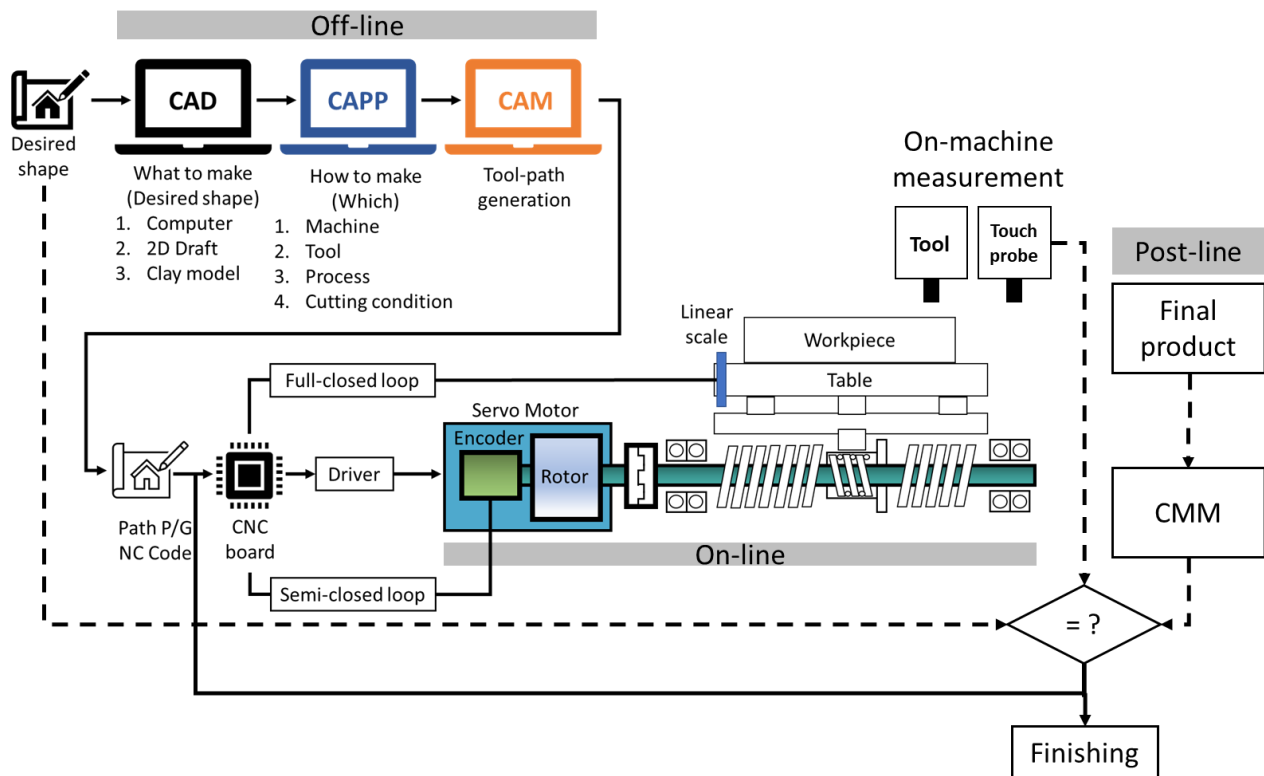
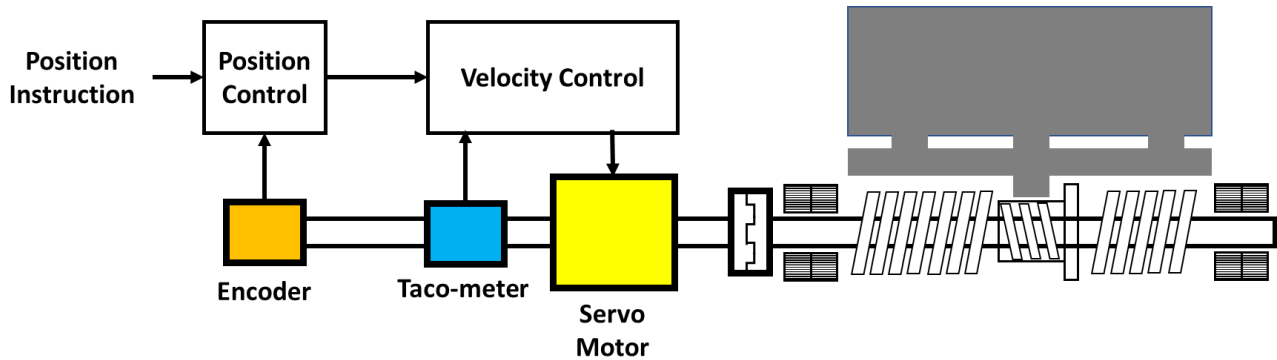


Figure 2.1: The Architecture of a NC machine tools and machining operation flow

The offline task is where the ideas are digitalized in 2d or 3d models and then, into G code. The characteristic of the models will affect the tool selection for the machine. At this very first step there are many software that support us to simplify the process. Then in the second step, the machine will be driven by the preferred software to create the final product. It can sound very simple as plug the machine as hit the start button but in fact there are many steps of calibration to be made. The more preparation in this step, the less of the post milling actions, as in third step, to be taken.

Nowadays, Computer Numerical Control (CNC) is no different from Numerical Control (NC), meaning a machine tool operating using a CNC system. One consisting of vacuum tubes, large-scale integrated circuits, and logic elements is called “Hard-wired NC”; It performs NC functions using electrical wiring. With the advances of technology in the capacity and availability of microprocessors, the NC functions are now implemented based on the software, creating a new era of CNC – “Soft-wired NC.”

## The components of the CNC machine



*Figure 2.2: Primary CNC machine units*

As shown in the figures above, one primary CNC machine consists of three units: The NC unit, which acts as the Human-Machine Interface and computes the information, the motor unit, and the driver unit. The NC unit itself is called the CNC system. From the hardware point of view, as a logical flow of the system, the output of the position control, which is the end function of the CNC system, is sent to the driver of the motor drive system. The driver will drive the servo motor with control of torque and velocity, and then the servo motor will move the workpiece as desired with the help of the transmission devices.



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## The NC unit

During the operation of the machine, the NC unit will continuously send an output signal instructing the driver, so we call it a loop. There are two basic types of control loop: a feedback control loop and a non-feedback control loop, known as a closed loop and open loop.

### ❖ Open-loop

Open-loop control has no feedback; therefore, it will not have the ability to adjust its movements. Open-loop can be applied when the need for control accuracy is not high, and as it will be instructed in step, a stepper motor is required for this control mode.

The structure of an open-loop system does not require any sensors or extra transmission for feedback signals, making it the simplest structure of all control methods. As mentioned before, the driver will be driving a system using step impulse, so the accuracy of this system is influenced by the accuracy of the stepper motor and transmission protocol.

### ❖ Closed loop



A Closed loop system, as mentioned before, has a continuous feedback signal to provide the system the ability to compare the desired value versus the actual value and, thus, process the error value. The system will work on eliminating these errors using a variable of methods, most commonly in the CNC systems, the PID control method.

Addressing closed-loop control systems, we usually also hear about semi-closed and hybrid loops.

### ❖ Semi-closed loop

The semi-closed loop is still a closed loop but with a different type of feedback signal. The closed loop for a specific control, for example, position control, will require the feedback signal to be also position feedback. In contrast, the feedback signal for a semi-closed loop can be anything that can convert to position using related formulas. As a result, the semi-closed loop is the most popular control mechanism. For example, a position detector is attached to the shaft of a servo motor and detects the rotation angle. The position accuracy

of the axis, based on the rotation angle feedback, significantly influences the accuracy of the ball screw that is in the linear plan. By transferring rotational to linear movement, we increase the ball screws' accuracy and practically overcome the problem with accuracy. If necessary, pitch error and backlash compensation can be used in NC to increase positional accuracy. The pitch-error compensation method declares that, at the specific pitch, the accumulation of positional error can be removed using modified instructions for servo drives. Moreover, the backlash compensation method claims that additional pulses corresponding to the amount of backlash are sent to the servo drive system whenever the moving direction changes. Recently, the Hi-Lead-type ball screw usage with a large pitch for high-speed machining has increased.

#### ❖ 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. When it is difficult to improve the stiffness in proportion to the weight of the moving part or decrease wasted motion in a closed loop, as in a heavy machine, the gain must be reduced. When the gain is small, the performance in terms of positioning time and accuracy suffers. In this example, we have the semi-closed loop, which detects position from a motor shaft, and the closed loop, which is based on a linear scale. Because the machine is not included in the control system, it is possible to regulate with high gain in the semi-closed loop. The closed loop improves accuracy by accounting for the mistake that the semi-closed loop cannot control. Despite its low gain, the closed-loop is well-behaved since it compensates for positional mistakes. Combining the closed and semi-closed loops allows for great precision and gain in an ill-conditioned machine.

## Kinds of controls in a system

Any feedback control system will consist of three independent loops for three parameters for each axis. The most favored loop, the outermost loop, is for position control. Generally, this loop is located inside the NC unit; the default settings of any device is for this control loop. The middle loop is the velocity control, and the innermost is the current control loop, both of them are located in a servo drive device. However, this is not the standard setting, and the locations can vary based on the designer's purpose.

For the machine's spindle, the feedback loop is not necessarily needed. But the velocity feedback control can be applied to maintain a regular rotational speed. In this project, we use a DC motor for the spindle, then the feedback method cannot be applied. In order to improve the performance of the machine, we will try to implement the use of an AC motor.

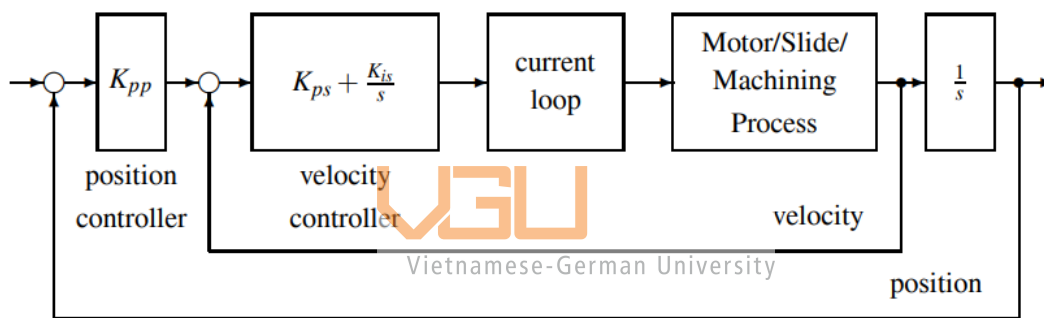


Figure 2.3: Three kinds of control loop in CNC

## The Motor Unit

The motor unit is the physical system that transforms the commands from the NC unit into machine movements. The Figure below shows the two primary mechanisms of a CNC machine: a servo-driving mechanism and a spindle-driving mechanism. In CNC machine tools, permanent magnet synchronous motors have been used as a servo to enhance performance. The Figure describes the servo driving mechanism that consists of a servo motor and a set of power transmission devices. The servo will carry out the given command from the NC unit by rotating as much as commanded. This rotation will be transmitted to the ball screw using the coupling. The ball screw will transform this rotation into the linear movement of a nut so that the workpiece can move linearly. Not only the position, but the servo can also control the velocity and the torque of the workpiece base on the NC commands.

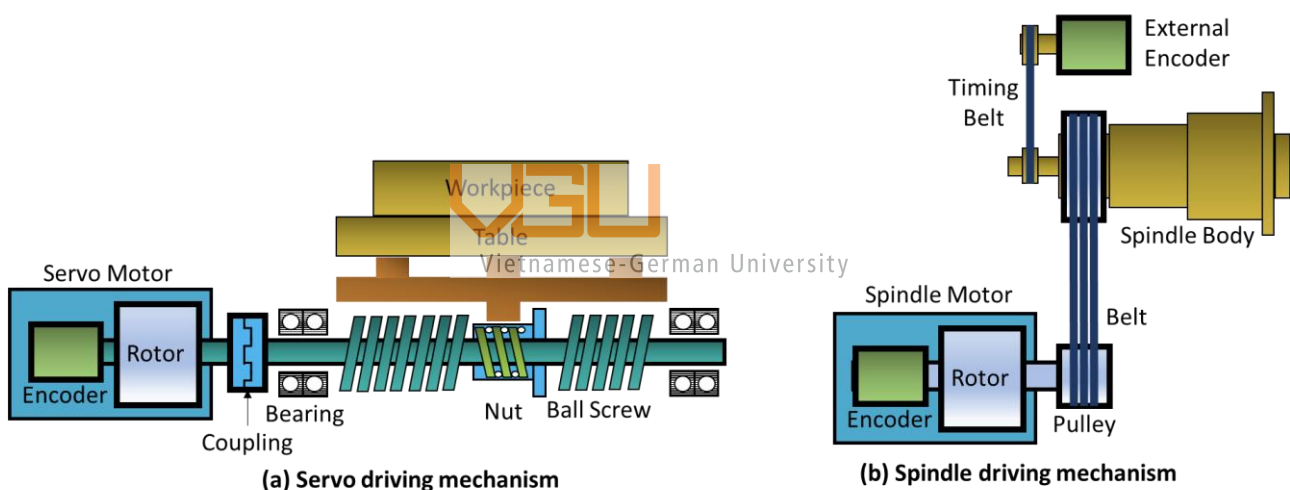


Figure 2.4: The Motor units

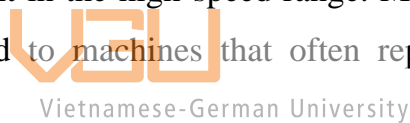
The second Figure shows the spindle unit, which comprises a spindle motor and a series of power transmission components. For large-scale machines, the spindle motor rotation will be conveyed to the spindle body via a belt and pulley system, with the velocity of the spindle body scaling up or down depending on the ratio of the two ends' pulley diameters. Instead of a belt, some machine tools employ gears to deliver power. On the other hand, power transfer via gears is unsuitable for high-speed milling. For high-speed spinning beyond 10,000 rpm, a direct drive, in which the spindle motor and spindle body (headstock) are directly coupled without a power transmission mechanism, has recently been used. This

method could also be applied for small-scale machines as it will help neglect calculations for extra torque and decrease speed loss during transmission.

The term “driving motor” refers to the servo motor, which moves the workpiece and the spindle linearly, and the spindle motor, which power the spindle.

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 size, weight, inertia, efficiency, maximum speed, and maintenance.

To control velocity and position simultaneously, the servo motor requires strong torque, high acceleration, and fast response at low speeds. For example, turning machines and machining centers will require high torque for heavy cutting in the low-speed range and high speed for quick movement in the high-speed range. Motors with low inertia and high responsibility are better suited to machines that often repeat jobs with relatively short machining times.

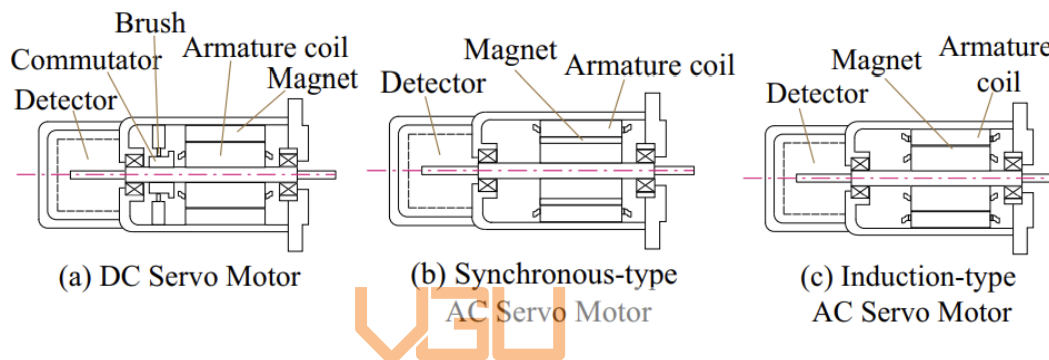


There are several key qualities that machine tool servo motors must have:

- Capability to obtain a suitable power output based on workload.
- The ability to react rapidly to an instruction.
- Dependable acceleration and deceleration characteristics
- Extremely large velocity range.
- The ability to safely manage velocity in all velocity ranges.
- Capability to operate continuously for an extended period of time
- The ability to accelerate and decelerate often.
- The ability to generate sufficient torque in the case of a tiny block (have a high-resolution range).

- High rotation accuracy and ease of rotation
- The ability to generate enough torque to stop.
- Longevity and dependability.
- Easy to maintain.

Several servo-motor types that are designed to satisfy the mentioned characteristics are listed in the Figure below: DC Servo Motor, Synchronous Type AC Servo motor, and Induction type AC Servo Motor, respectively



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 Figure 2.5: Types of servo motor

#### ❖ DC Servo Motor

The DC Servo Motor is more sophisticated than the AC Servo Motor, as seen in the Figure. A DC servo motor has two main components: the stator, which is the static part and consists of a cylindrical frame and the magnet, and the rotor, which is the revolving part and consists of a shaft and brushes. The commutator and rotor core (metal supporting frame) are coupled to the shaft, and the armature is wrapped inside the rotor metal supporting frame. Current is supplied through the commutator by a brush made from the armature coil. A detector, 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, we 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

Unlike the DC servo motor, the magnet of the synchronous-type AC servo motor is attached to the rotation part while the armature coil is wound around the inside of the stator. It is like they switch positions with each other. The end of the armature coil connects with a lead wire to fetch the current from the outside without the stator. Because of this structural characteristic, there cannot be any attached brush inside the servo, which leads to the name "brushless servo motor". This structure also enhances the cooling process of the stator by allowing the cool-down process to happen directly from the outside, giving the servo some resistance to temperature increase.

There is no limit to maximum velocity that a synchronous-type AC servo motor can achieve thanks to a rectification spark, hence, obtaining a good torque characteristic in the high-speed environment.

In addition, because there is no brush, it can be operated for a long time without needing maintenance. The only point that this type of servo can have the same as the DC servo motor is that it also uses the optical encoder as a detector of rotation velocity, but not a tacho-generator. Instead, the AC servo motor uses a resolver.

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 sensing 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

The structure of an induction-type AC servo motor is quite similar to that of a synchronous AC servo motor. The distinction is that the stator in this type of AC servo motor is made up of a frame, a core, an armature coil, and lead wire, whereas the rotor is made up of a shaft and a conductor-built rotor core. A relative position detector between the rotor and stator is not required for an induction-type AC servo motor. 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 strengths, weaknesses and other characteristics of the mentioned servo motors

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

*Table 2.1: Servo-motor summary*

## ❖ Encoder

The device that usually comes along with servo motors to detect the change of position for position control is called an encoder and, generally, is built right into the end of the power transmission shaft. Using the encoder, we can also control other parameters, such as velocity, torque, etc., related to changes in an equation. For example, the generated pulses in a unit of time or the interval between pulses can represent the velocity of the servo. The encoder is classified after the material type, magnetic or optical, and after function, absolute or incremental. In this project, the encoder attached to the servo is the magnetic-type and either incremental or absolute because the function is affected by the Electrical encoder with fixed resolution inside the servo drive.



## The Driver unit (Servo pack)

### ❖ Servo drive

A servo drive is an electrical amplifier that continuously checks the feedback signal from the servomechanism and adjusts to achieve the desired behavior. The command signal typically reflects the desired location but 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 an actual system, proper configurations help the servo operate at a velocity approximately equal to the velocity signal being processed by the servo drive. Several gain parameters, such as proportional gain or stiffness, derivative gain or damping, and feedback gain, can be adjusted to achieve or linear the desired performance in a performance tuning process. Although many servo motors come in the same pack with their specific drive, many drives are now compatible with various motors. Servo drives in industrial process digital or analog signals; some can even handle 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 when mechanisms must adapt to various environments with minimal effort. One disadvantage of digital drives is their high energy consumption. However, because many digital drives currently are built with batteries to check battery life, this can be quickly remedied. 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 signals ranging from -10Volt to +10Volt or 4mA to 20mA. These control signals can be manually adjusted manually with potentiometers or specific conditions bonded with buttons set in the setting. Most analog drives interact with feedback signals produced by a tach generator to measure and produce a resulting torque demand, which requests current in the mechanism depending on the feedback loop. Servo drive is

referred to as a four-quadrant drive because of its ability to brake, accelerate or decelerate in both directions. Analog drives consume less energy than digital ones and can sometimes offer performance as high as digital drives.

❖ 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.

## Calculations

### Milling speed and Feed forward calculation

In order to determine the roll per minute (spindle speed) and feed forward rate (IPM) for a milling operation, we need to have the tool's specification such as number of teeth, diameter and it feed per tooth.

The cutting feed is calculated as in the equation:

$$\text{Feed per tooth (IPT)} \times \text{Number of teeth} = \text{Cutting feed (IPR)} \quad (2.3)$$

Using the cutting feed, we then multiply with the spindle speed to get the feed forward rate, shown as below:

$$\text{Cutting feed (IPR)} \times \text{Spindle speed (RPM)} = \text{Feed forward rate (IPM)} \quad (2.4)$$

### Drilling speed and Feed downward calculation

To get the feed downward rate, we also use the equation 2.4 with the cutting feed equal to 10% of the tool diameter.



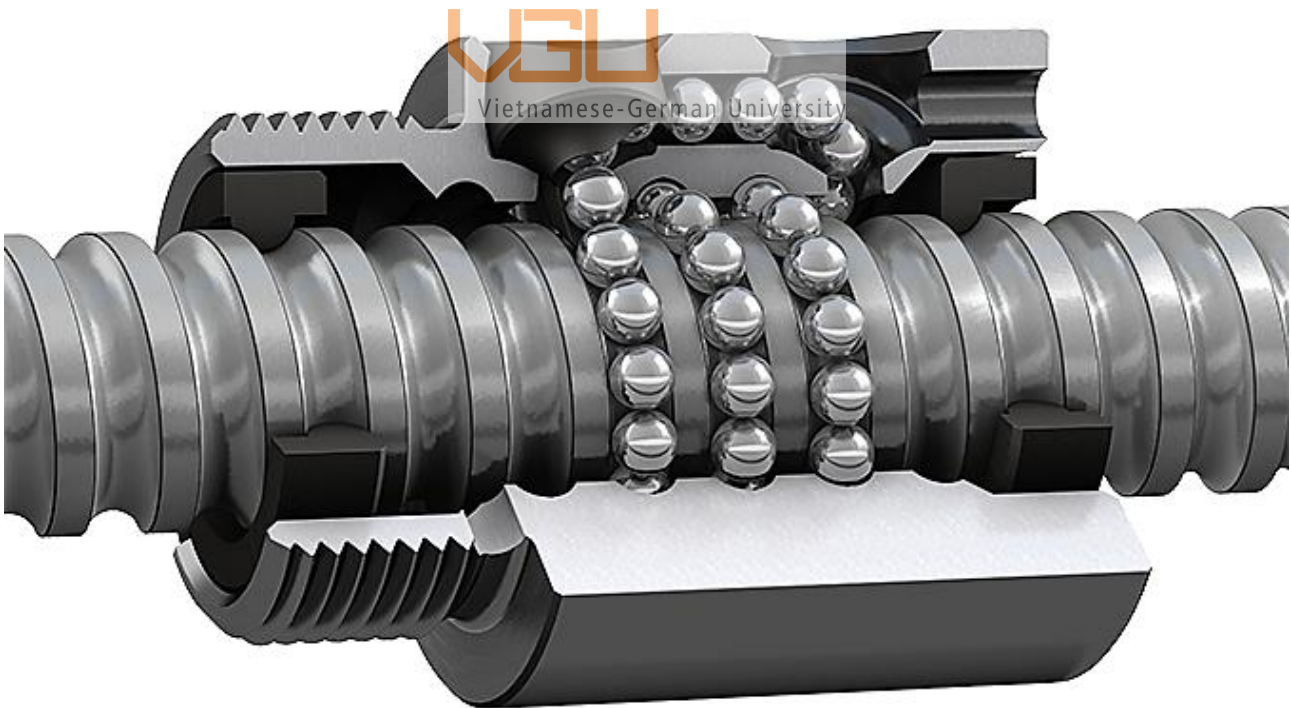
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## Hardware

### Linear movement

#### Ball screw

A ball screw is essentially a lead screw that is powered by a ball bearing; it is used to move the table or tools installed on the tool's axis and converts the servo motor's rotating motion into linear movement. The ball screw is typically used in conjunction with two Linear Movement (LM) guides to improve the accuracy, smoothness, and stability of the linear movement. They are all parallel in the same plane with the desired linear movements and use the nut mechanism to sustain them. A mechanism inside the nut allows the ball bearing to rotate continuously and move from one end to the other. Because these balls make contact with the nut and screw, the rotation creates a rolling contact between the metals, reducing starting friction and sliding friction and smoothing the movement even at low speeds. Furthermore, because the lead of the screw is related to the displacement unit of the nut, it is feasible to prevent backlash by using a customized bigger ball or double nut.



*Figure 2.7: Ball screw mechanism*



## Coupling

Coupling is a mechanical component that connects the servo motor shaft with one end of the ball screw and transfers the rotational movement from the servo to the ball screw. One other purpose of coupling in the system is that when the two shafts are joined, their center should be identical; however, it is not very practical during practice. The couplings should be insensitive to misaligned rotation centers to better stabilize the movement. These are called flexible couplings, as shown below in the Fig, with evenly distributed slits so they can bend at a slight angle in any direction.



*Figure 2.8: 8\*8mm RS-flexible coupling D19 L25*

## Belt and gears

The belt and gear are also the mechanical components to transfer the rotation movement from the motors to the rotating body. They are primarily used to link the spindle motor with the spindle body. The belt system is used in terms of power through the friction between the pulley and the belt. In the designs requiring higher torque at a lower speed, the gears are used as a transferring method and a speed reducer. In one transmission system there can be a single mechanism or a compound of multiple mechanism. Since these mechanical components do not directly connect the two-part parts, they are called the "indirect driving method."





Figure 2.9: A simple belt and gear system



Figure 2.10: Type of gears

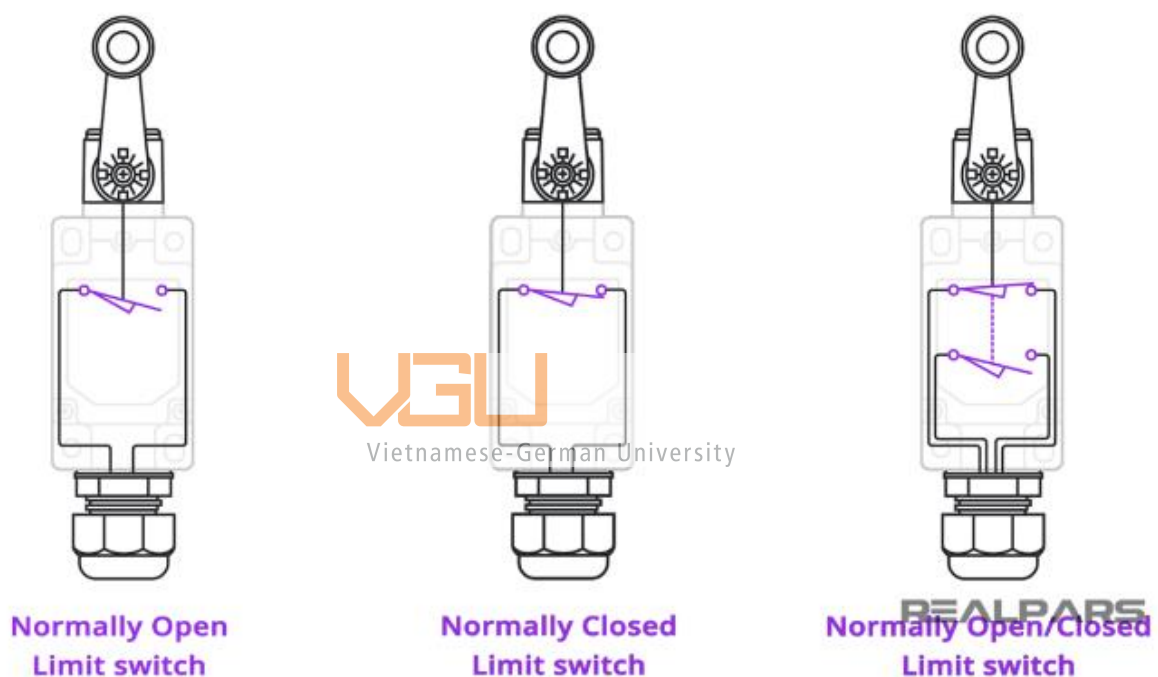
However, the indirect driving method is not suited to high-speed machining, not to mention maintenance and noise. Nevertheless, since the price is reasonable, it is a better option in some instances.

The direct method using coupling is preferred as backlash does not exist, and the amount of runout is relatively tiny. In addition, it provides the ability to suppress the variation of torque and is easy to operate.

## Limit switches

The limit switch is an electro-mechanical switch consisting of an actuator mechanically linked to an electrical switch. Based on the motion of a machine part or the presence of an object in contact with the actuator, the switch will operate, causing an electrical connection to make or break.

They are available in several configurations: NO - Normally Open, NC - Normally Closed, and combined, as shown in the Figure below.



*Figure 2.11: Types of limit switches*

The name "limit" is because they are first used to define the limits of travel and an emergency stop. However, they are becoming available in many applications and environments due to their ruggedness, reliability, and ease of installation.

Standardized limit switches we mainly use are industrial control components manufactured with four main operator types: lever, roller plunger, and whisker.

## Switching mode power supply

The Switched-mode power supply is a power converter with high efficiencies (up to 90%), small in size, and widely used to supply power for sensitive electronic devices. It utilizes



switching devices such as MOSFETs, capacitors, and inductors to turn on and off at high frequencies and stabilize the power supplied into the system. They are categorized based on the input and output voltage type, and the range can vary between 12V to 220V.

## Controller Akz250

AKZ250 is a custom motion control main board designed to support all Mach3 versions fully, and Windows versions and also play a hand in software limitation and backlash. The board's design, with sixteen general-purpose inputs with corresponding indicators, can handle up to sixteen limit switches or devices with the same functions. It has its own onboard, isolated power supply to operate only using the USB connection; however, an external power supply can be applied to reduce the USB load. This high-cost design, containing ten high-speed optocouplers with 10MHz, and twenty-four general optocouplers for isolating all input/output signals, can provide high performance and a stable system. The output control commands and the input feedback signals use the same USB connection but require no USB drivers and even support for a USB hot-swapper as the card is monitoring the USB connection status at all times. Feed rate, spindle speed rate, or jog rate can be controlled via the attached adjustment knob and observed via Mach3 HMI.

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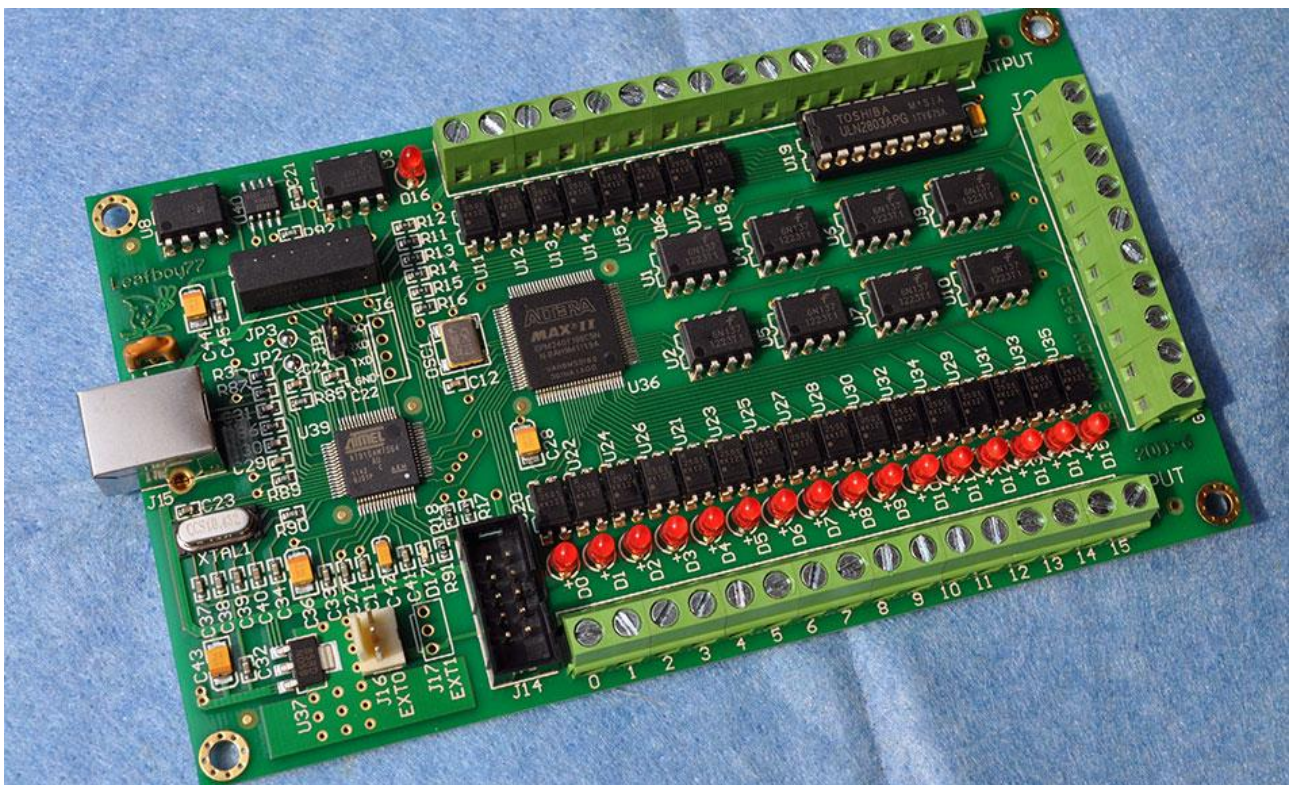


Figure 2.12: Controller AKZ250 board

## Software

### Mach3

Mach3 is the flagship of ArtSoft products. There are two released versions: the Lockdown version, which is a stable, static release recommended for new users, and the Development version, which contains up-to-date features as there is more patch released for this version. We only need to use the Lockdown version for this specific project as the code line limitation is the same for both versions without a license.

Mach3 is a program that turns any computer into a CNC machine controller. It offers many amazing features and is a terrific bargain for individuals requiring a CNC control bundle. Mach3 operates on most Windows PCs by processing G-Code to control motor movements (stepper & servo). Because of its many sophisticated capabilities, such as being very configurable, it is now the most intuitive CNC control software available. It has been utilized for many applications with many types of gear.

### Inkscape

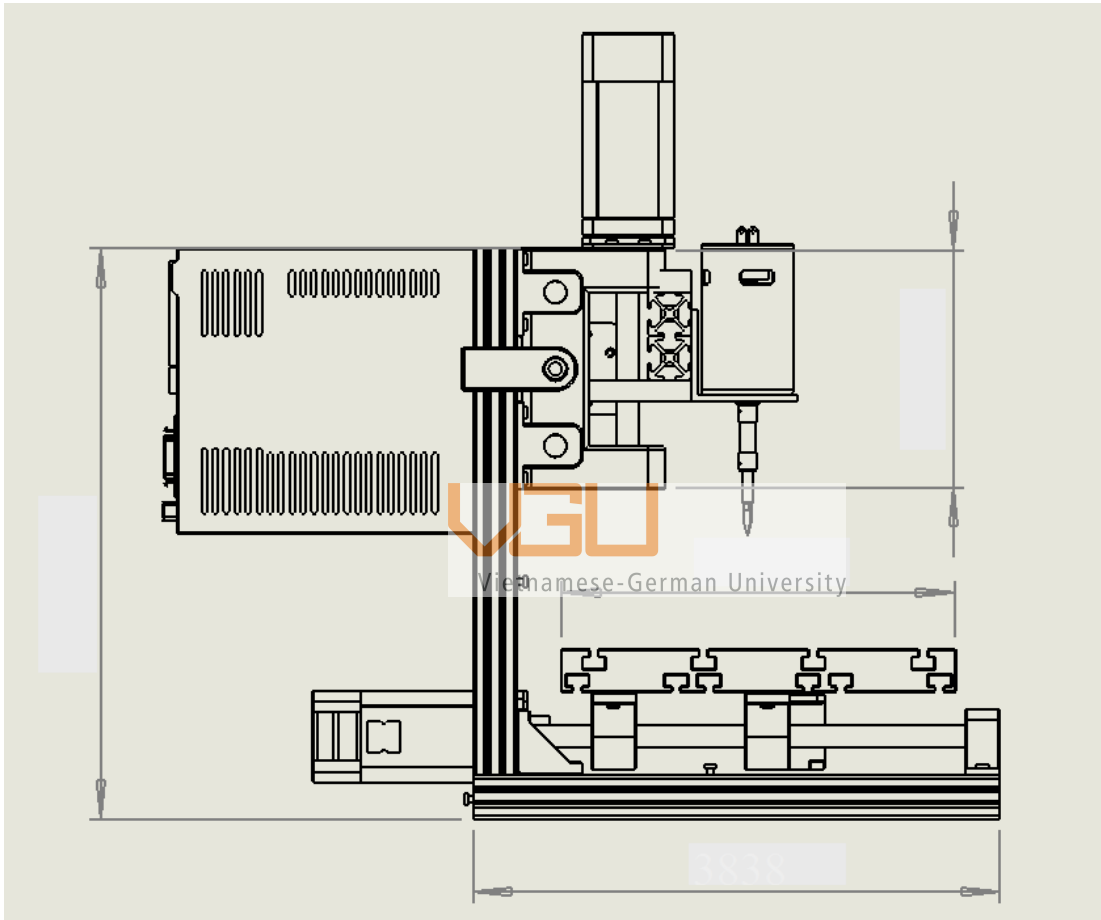
Inkscape is an open-source program specialized in vector drawing. Even though it seems to be infamous, it is equivalent to other popular packages such as Adobe Illustrator, CorelDraw, or Affinity Designer. The latest version is 0.48 and is constantly being developed and upgraded. Unlike other programs mentioned, Inkscape supports other abilities that can be done with vector graphics rather than optimizing the quality of tools that help create vector graphics. Since it is "open source," the user can edit the source code to improve the program's ability. CNC-supported modification for Inkscape can easily be found, and it is implemented inside the program itself and requires fewer configurations and installations.

The project website includes tutorials, guides, and forums and can be found here: [www.inkscape.org](http://www.inkscape.org).

## Chapter 3: Detail design of the CNC machines

### The Design and CAD model

The first thing to be handled is the design of the machine. We have a couple of sketches for sample modeling and dimensioning on paper and, later on, created the first model in Fusion 360. The calculations for this build are based on one other project. Altogether, the first CAD model of the machine is as below



*Figure 3.1 The 2D drawing of the CNC milling machine*

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



## The Frame and the base

### Frame

The frame serves as the machine's solid foundation. The gantry will be attached to the frame by leadscrews and will eventually be supported by a work surface. It also houses the x-axis stepper motor and spindle.

The frame consists of twelve 20x20mm aluminum profiles, two 20x40mm aluminum profiles to clamp the spindle on Z-axis, and twelve 20x20x20 corner pieces. These profiles are cut to the desired length and bolted together using the corner pieces to form the machine's frame.



*Figure 3.2: The Frame of the machine*

We decided to enhance the performance of our machine by having two support rods with bearings to share the force apply on the ball screw. The set-up is as in the two figures below.



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*Figure 3.3: The build of X axis linear movement.*





*Figure 3.4: The frame and the Base X axis.*



## **The Y-Z axis**

The gantry is the mechanical part on the Y-axis to support the spindle motor above the workpiece. Initially, the gantry was the same as the design, but it was too crowded to mount everything on just one vertical plane, so we came up with a new design with four support profiles. This build was much more muscular than the initial one and provided more space to mount the drives and controllers.

However, high gantries have a drawback. They function as levers on guide rails, but by making the side plates longer, they bend more easily. As stated in the project scope, most of the work I intended to undertake with the CNC required machining wooden items. A typical vise for the machine would be 60 mm tall. Because the thickest blocks of sample easily available at present are also 60 mm in height.

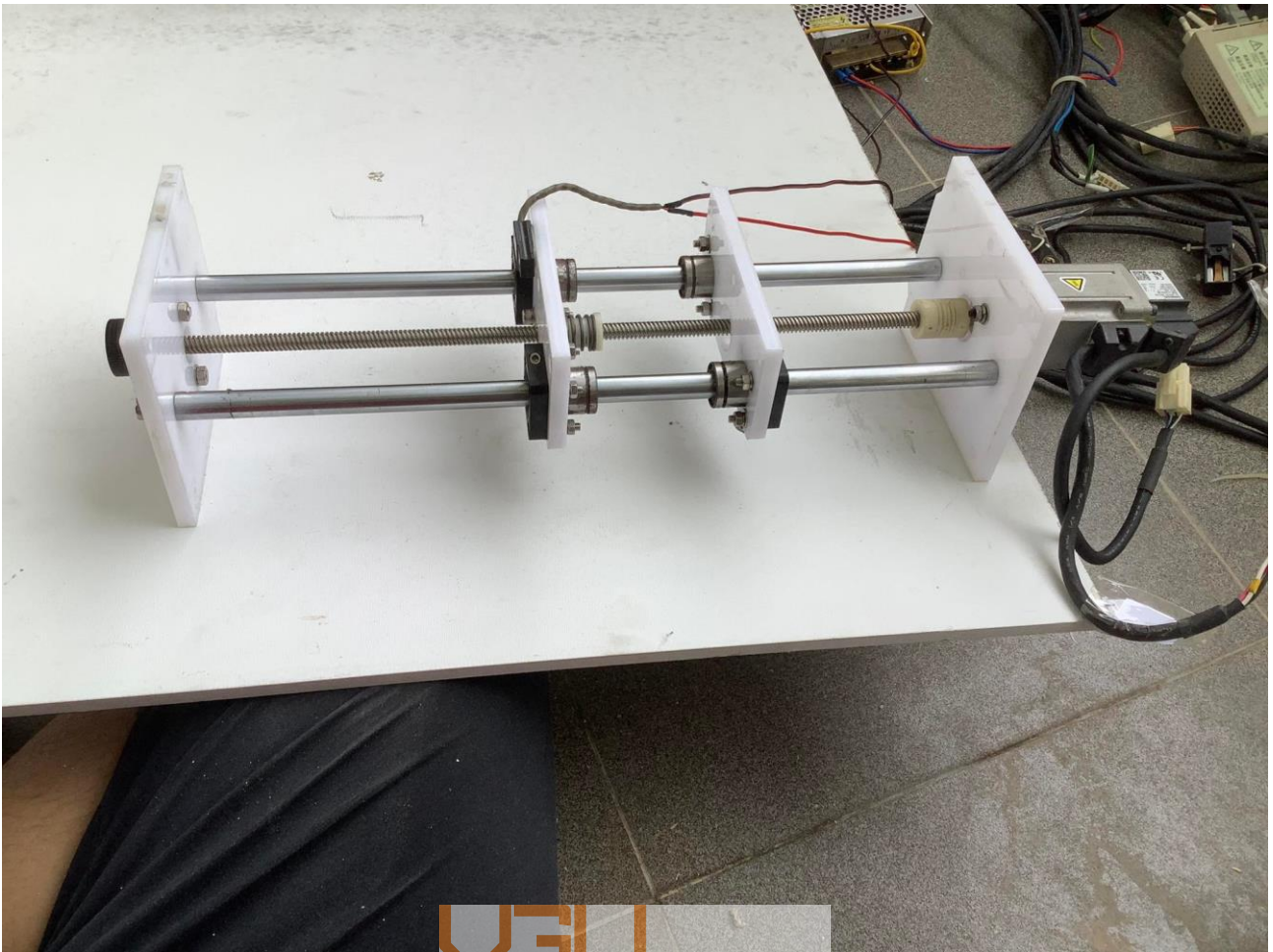
Four of the frame's twelve 20x20mm metal profiles are used to support the y-axis. It is held in place between the side plates by two basic Bakelite mica plates. They are attached to the side plates on the exterior. The z-axis and spindle are mounted on the y-axis.

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The same bearing blocks that support the x-axis are employed here as well.

## **Y axis linear movement**

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



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*Figure 3.5: The Y axis.*

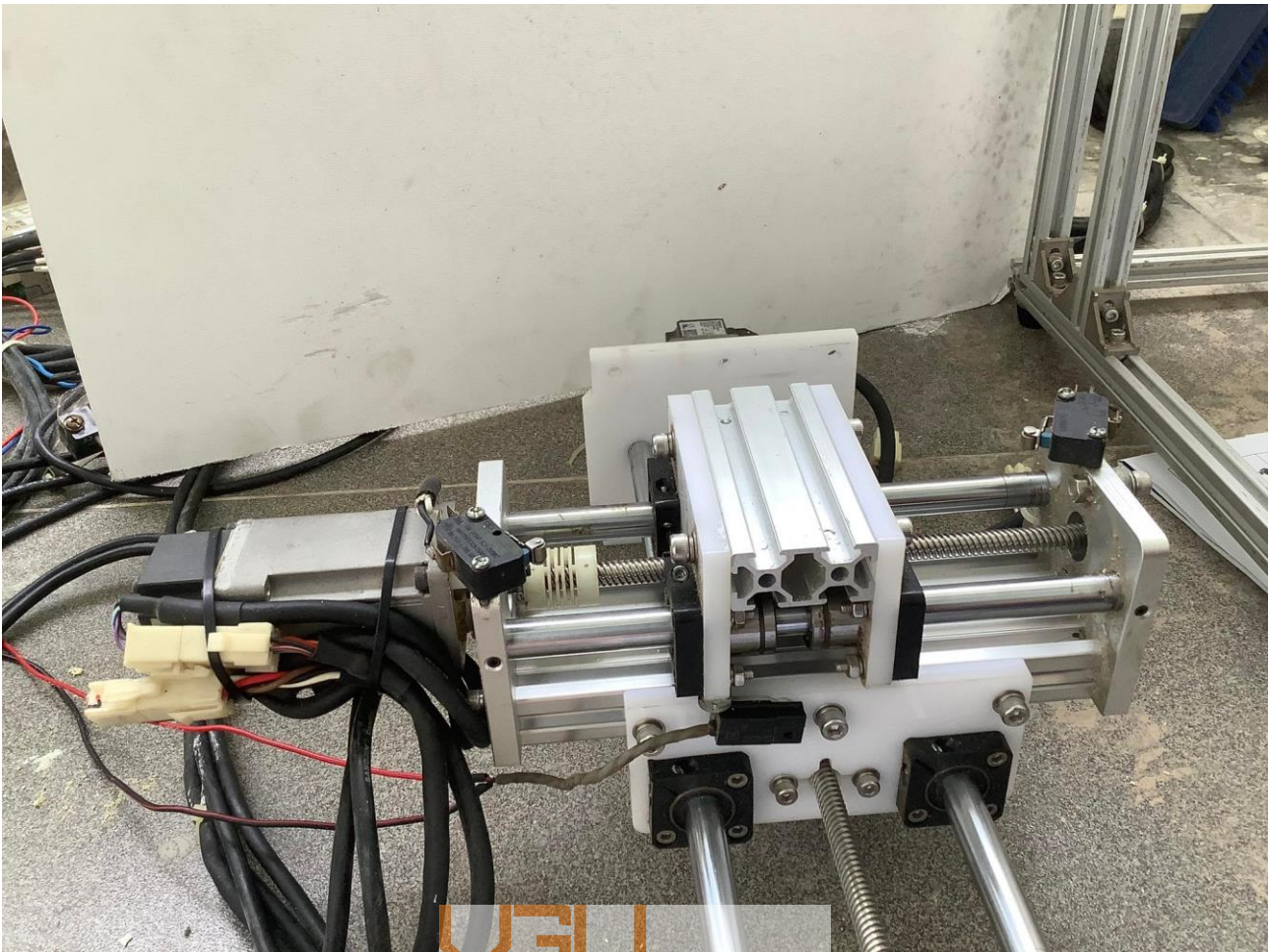
### **Z axis linear movement**

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



*Figure 3.6: The Z axis with mount part for Y-Z connection.*





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*Figure 3.7: The connected Y-Z axis.*

## **Spindle Mounting**

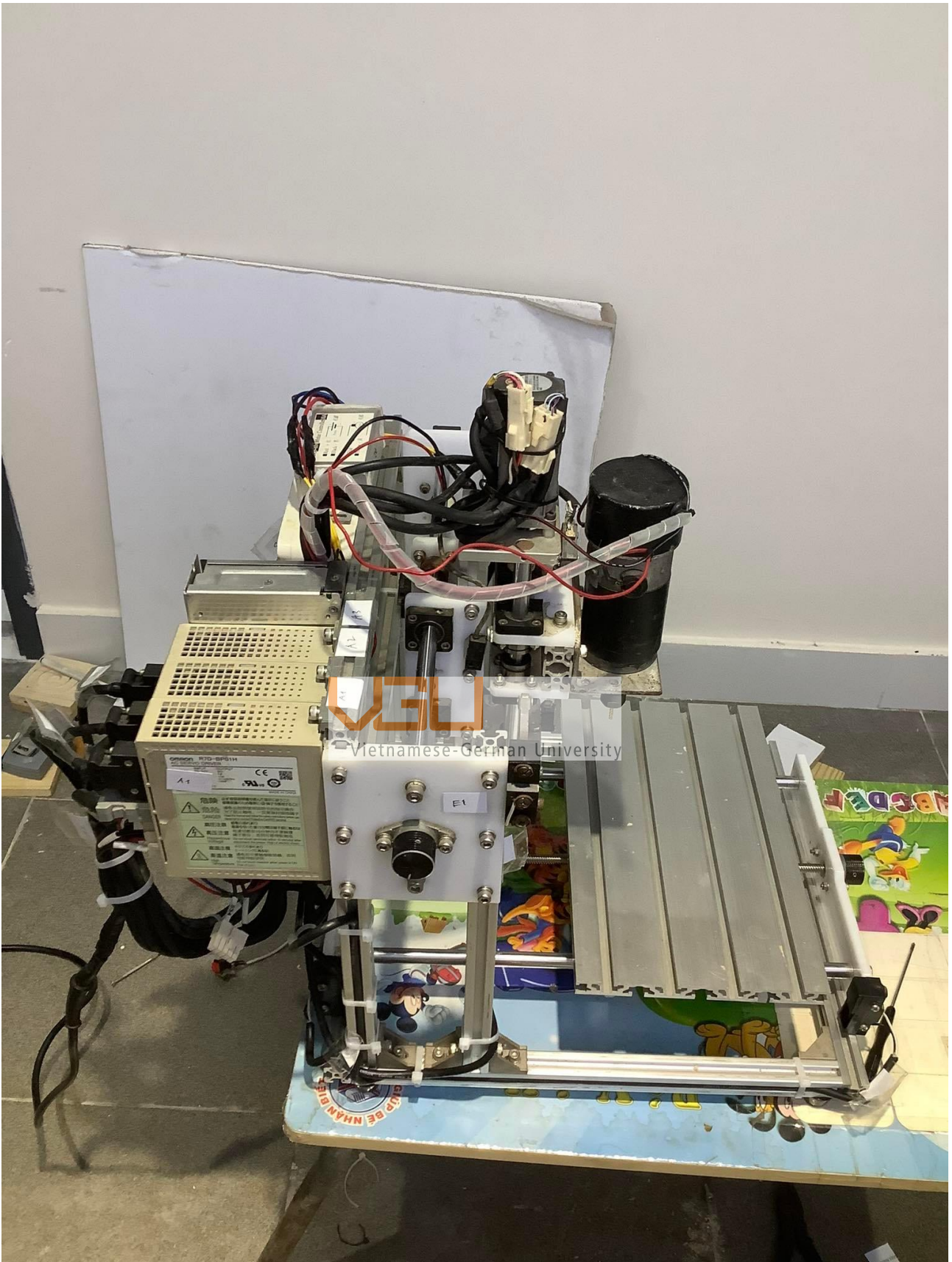
The z-axis motor mounting comes next. It comprises a y-axis-mounted front plate, two Bakelite plates, a motor mount, and a back plate. Two linear leadscrews for the z-axis were attached to the front plate, onto which the milling motor mounting plate and runner blocks were inserted.

The bearing for the z-axis spindle is installed in the motor mount. The Z-axis spindle nut was directly connected to the milling motor mounting plate. The backplate accommodates the y-axis spindle nut positioned on the interior.



*Figure 3.8: The machine with all axes mounted on.*





*Figure 3.9: The machine with all controller mounted on.*

## Chapter 4: Build of the machine

### Bill of materials and Machine specifications

#### Bill of materials

Item no.	Parts	Details	Quantity
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

## Machine specifications

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

## 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, we have selected the components that can optimize one power supply and are ready to go with just one plug.

## Power

The main components in the electrical system are:

- Stepper motors
- Stepper drivers
- Power supply
- Breakout board
- Emergency stop



Since I have to test the wiring and connection of the machine with computer, I temporarily mounted all the drivers and power supply on a open board. The enclosure is in the making.



Figure 4.1: The wiring of the whole machine

Since I had a lot of difficulties in finding a proper scheme with the needed components, I tried to make everything clear in the infographic below with just main component for basic NC operation

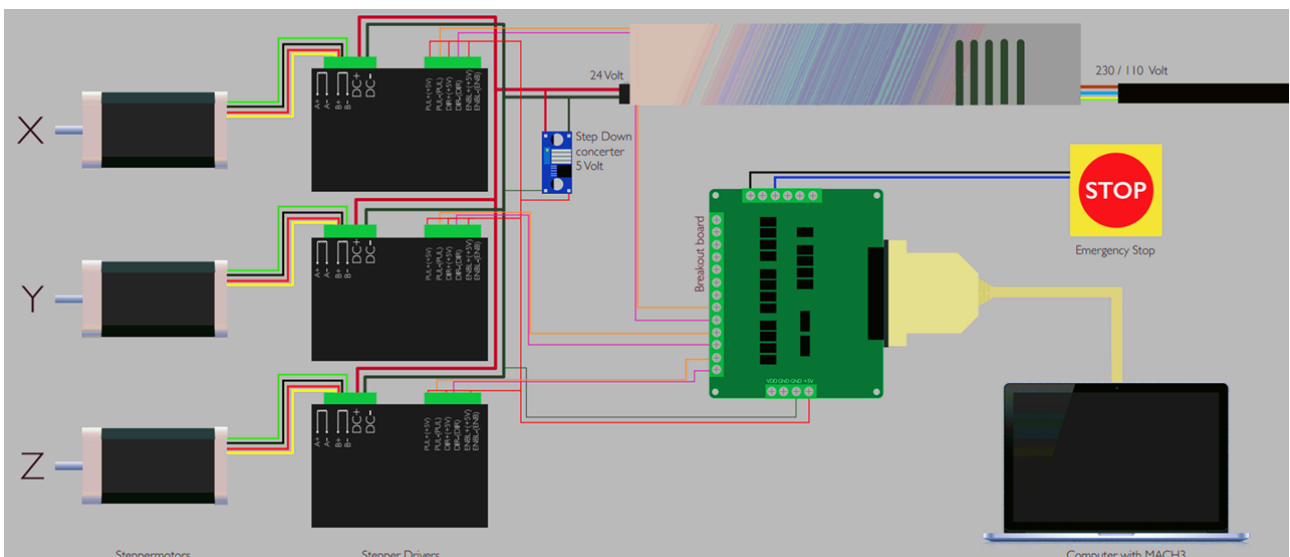


Figure 4.2: Wiring schema of the machine.

## Controllers

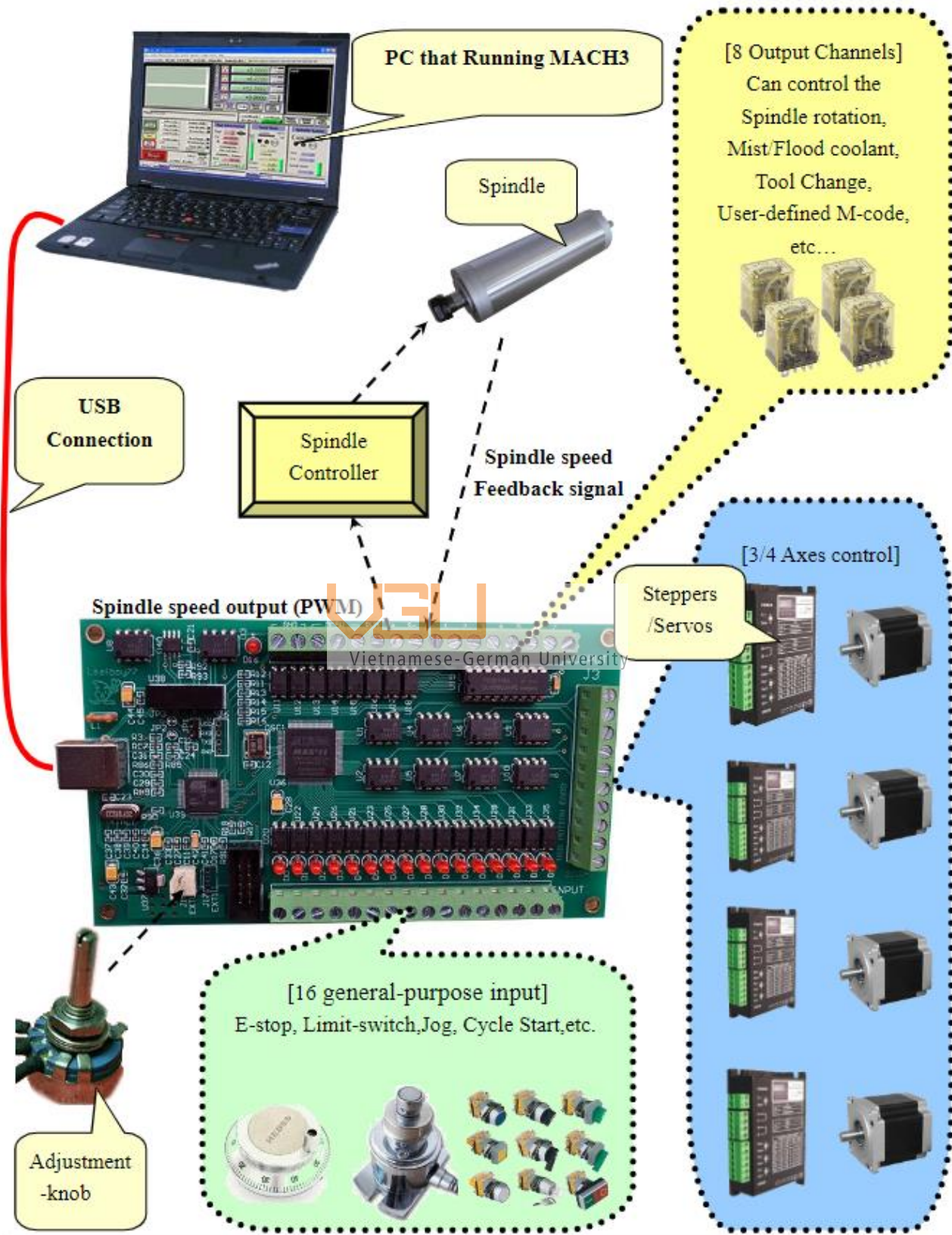


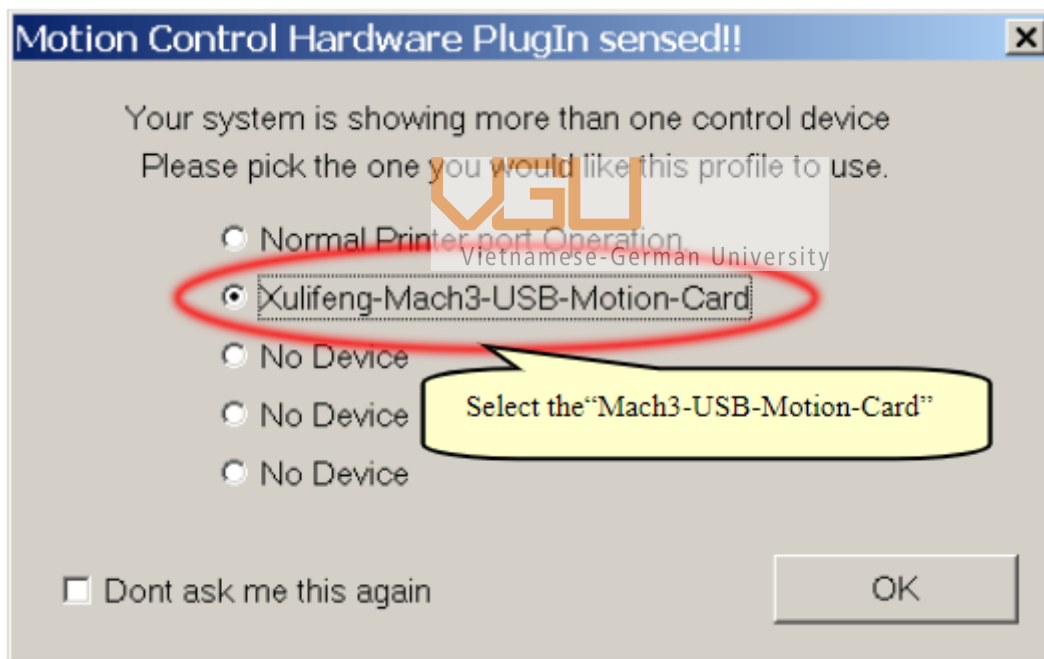
Figure 4.3: Wiring for all component signals

## Programming

### Mach3 setup

Mach3, unfortunately supports only PCs operating in windows and requires specific external motion controllers as plugins to control the machine. The plugin can be found as “UsbMove.dll” or “Xu Lifeng Mach 3 Motion Card USB.”

After we have finished installing Mach3, the plugins need to be downloaded and extract into the folder plugin of Mach3 as follow “(Install folder)/Mach3/Plugins”. We then need to have USB connection between the PC and the machine already, this way the software can sense the connection and a dialogue will pop-up for us to choose the motion card. Note that if there is no USB connection yet the dialogue will not pop up and the default mode will be selected.



*Figure 4.4: The dialogue to choose motion card.*

Depending on how many axis the machine going to use, we can enable the corresponding Ports and Pins. With motion card selected the order of Step-pin# and Dir-pin# doesn't really matter so we can ignore as default. The configure can be done as the figure 4. shown below.



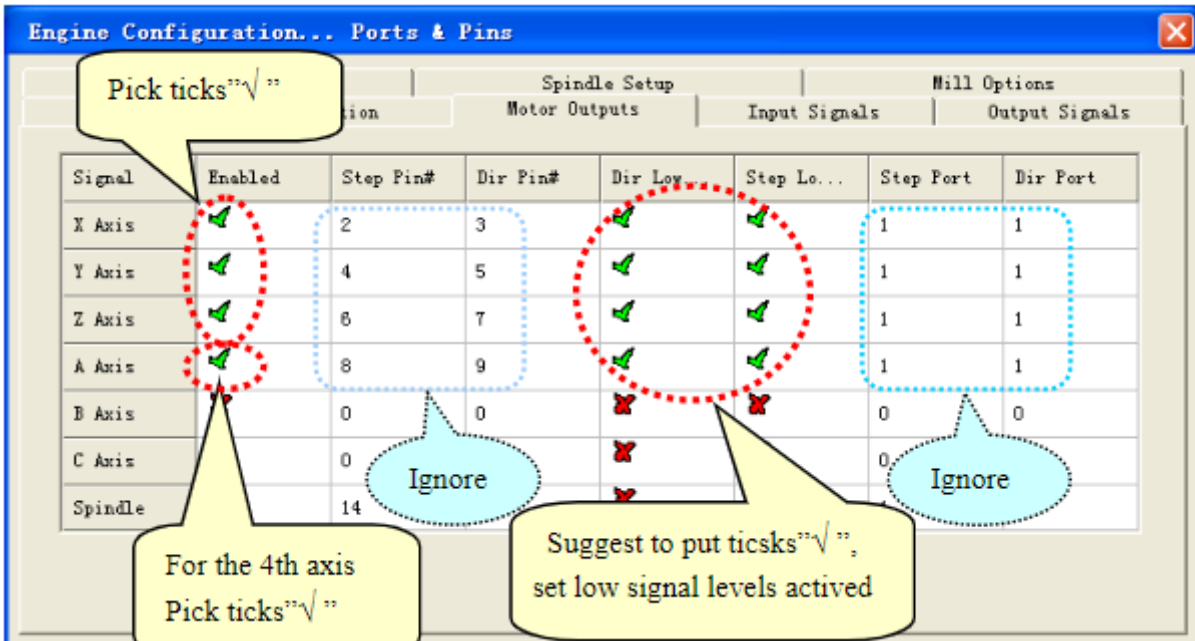


Figure 4.5: Ports and Pins configuration

Motor tuning setup is an advanced setup and normally does not require any change, default value is good enough. However, it still can be set up with explanation as Figure 4. shown below in case we need some parameter to match with our calculation or expectation.

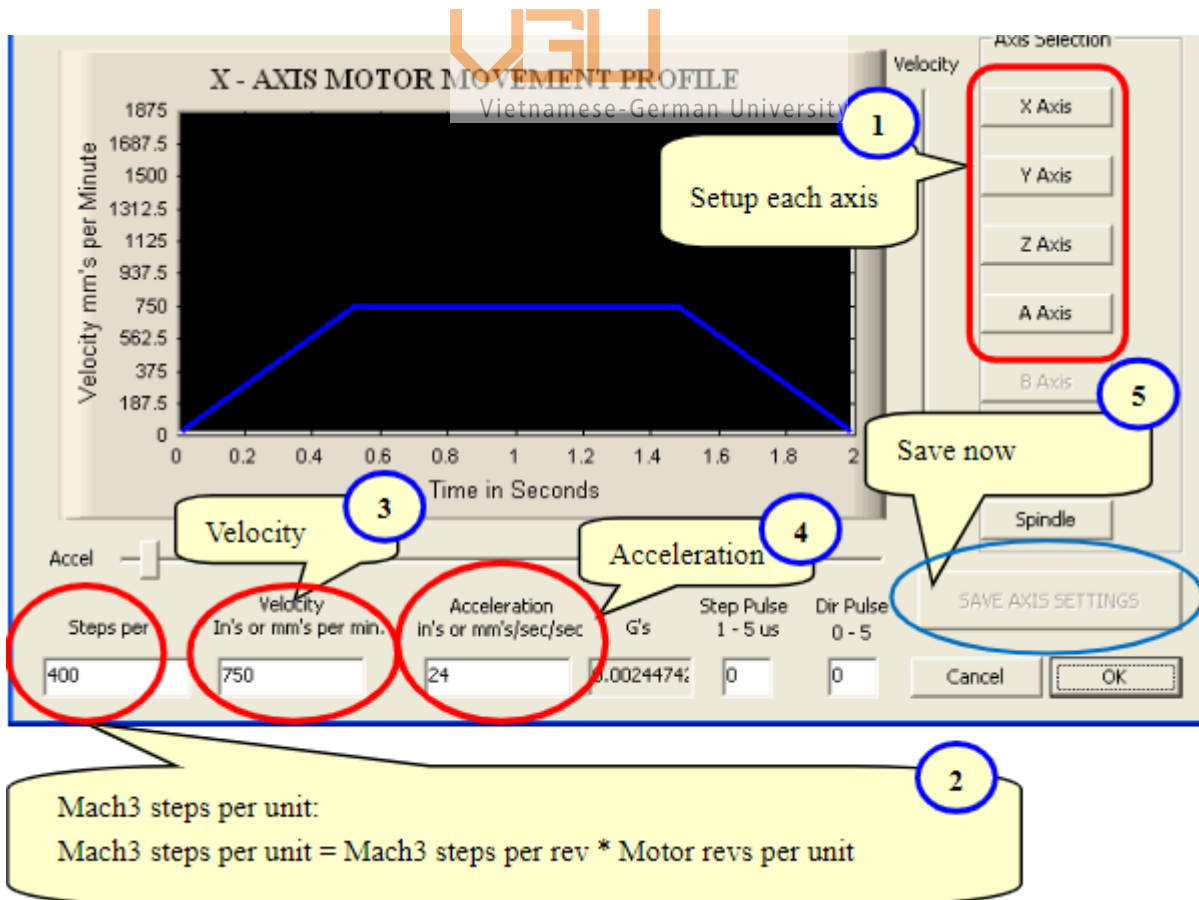


Figure 4.6: Motor tuning and setup dialogue

## G-code

The most extensively used numerical control (NC) programming language is G-code (also RS-274), which has various versions. It is mainly used to control automated machine tools in computer-aided manufacturing.

G-code is a language used to instruct computerized machine tools on how to manufacture something. The "how" is determined by g-code instructions sent to a machine controller (industrial computer), which informs the motors where to travel, how quickly they should move, and what path to take.

G-codes are any words in a CNC program that begin with the letter G. They are also known as preparation codes. In general, it is a code that instructs the machine tool on what type of action to take, such as:

- Rapid movement (transport the tool as quickly as possible in between cuts)
- Controlled feed in a straight line or arc
- Set tool information such as offset
- Switch coordinate systems



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Even though we do not focus on programming G-code in this project, understanding how it work helps in increasing performance of the machines as we can interfere with the code.

At instance, G-code can be complicated since it is just lines of numbers and some symbols. But these lines in fact, have the same structure. The numbers are Cartesian coordinates and the letters either stand for command or name of the axis. Usually, G-code can be divided into blocks of functions and are arranged in the following order:

- Program starts
- Load tool
- Spindle on
- Coolant on

- Safe Z
- Rapid to start position
- Machine operation
- Coolant off
- Spindle off
- Safe Z
- Safe X-Y
- End program

For programs that have ability and require more than one tool, the steps from 2 to 11 will be repeated for each tool. The G-code can be simply edited using any common text editor like WordPad or Note Pad. The figure below shows an example of a G-code project opening in WordPad.

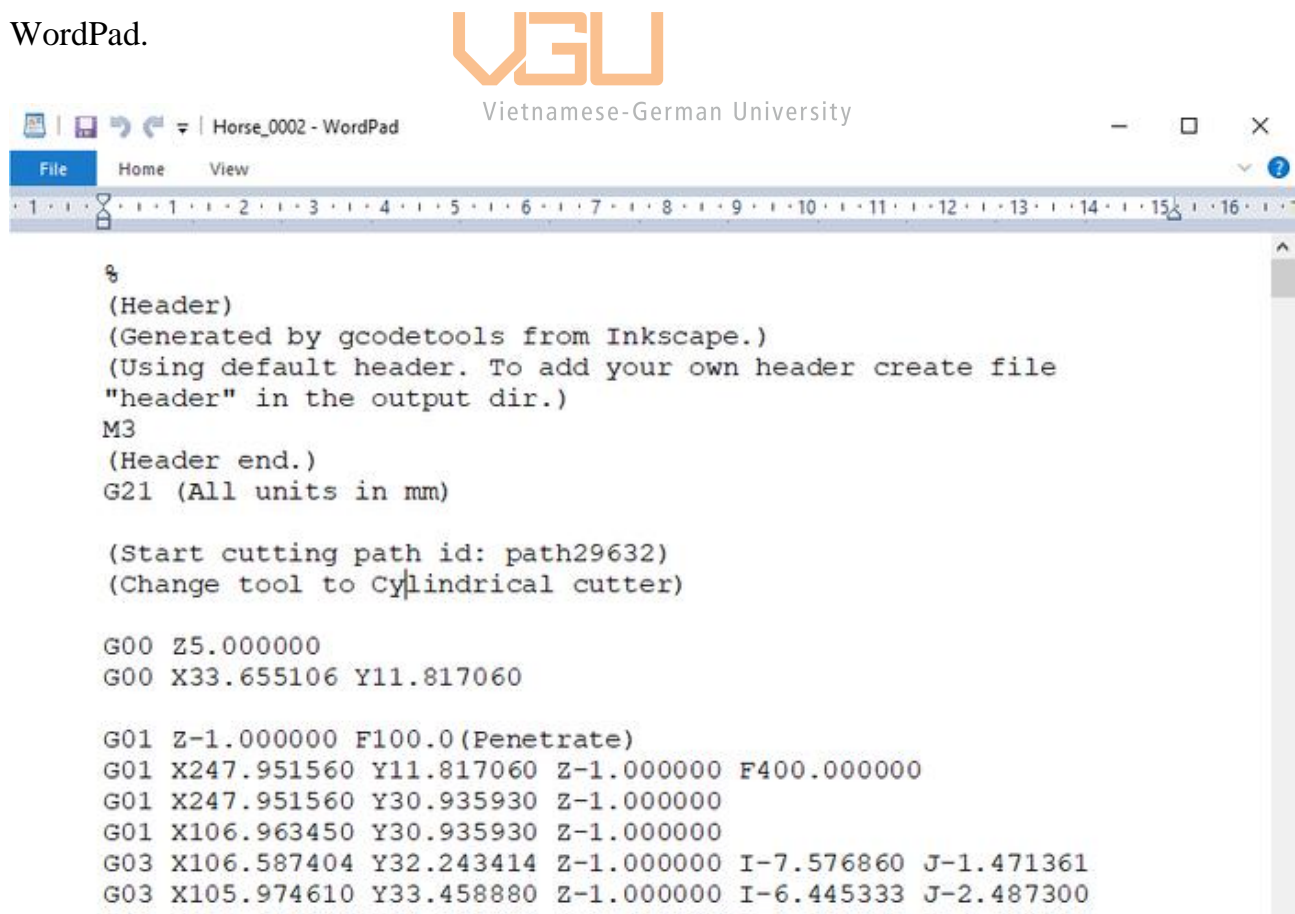


Figure 4.7: Example of a G-code file

These lines following the same structure:

G## X## Y## Z## I## J## F## (comments)

First there is the G command to indicate the path that the machine will have to follow from the current position to the XYZ coordinates. The IJ coordinate is the offset coordinates from the current position, these two coordinates help in movement path that require extra point, for example circular movements.

There are some other commands, which are not very common, start with M, H, T, F, S and usually stand alone in one line as for setting up the tool before any cutting happen. For different software it is better to look into its own example to know what commands it normally use if there is no information online, a set of commonly used G code explain is shorted as below.

Code	Meaning
G0	Rapid motion. Use for positioning the machine for non-milling moves
G1	Line motion at specific feed rate
G2	Clockwise arc
G3	Counterclockwise arc
G4	Dwell
G28	Return to home position
G40	Cutter Diameter Compensation (CDC) off
G41	Cutter Diameter Compensation (CDC) left
G42	Cutter Diameter Compensation (CDC) right
G43	Tool length offset (TLO)
G54	Fixture Offset#1
G55	Fixture Offset#2
G56	Fixture Offset#3
G57	Fixture Offset#4
G58	Fixture Offset#5
G59	Fixture Offset#6
G80	Cancel drill cycle
G81	Simple drill cycle
G82	Simple drill cycle with dwell
G83	Peck drill cycle
G84	Tap cycle
G90	Absolute coordinate programming mode
G91	Incremental coordinate programming mode
G98	Drill cycle return to Initial point (R)
G99	Drill cycle return to Reference plane (last Z height)

Table 4.3: Common G-codes

Code	Meaning
M0	Program stop. Press Cycle Start button to continue
M1	Optional stop. Only executed if Op Stop switch on the CNC control is ON.
M2	End of program
M3	Spindle Clockwise
M4	Spindle Counterclockwise
M5	Spindle Stop
M6	Change tool
M8	Coolant on
M9	Coolant off
M30	End program and press Cycle Start to run it again.

*Table 4.4: Common M-codes*



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# Chapter 5: Experiments

## 2D milling samples

### The general CNC workflow

Now, although each CNC Milling machine set-up technique is slightly different, these generic steps that CNC machinists use on a daily basis for a 3-axis vertical CNC Milling machine are discussed here.

#### 1. Begin with CAD model/ Vector graphic.

#### 2. Establish Job parameters including CNC coordinate system and stock shape/size.

CNC machines compute motion for each operation by interpolating from the start position to the end position, including intermediate points if required. The CNC machine does this by having the origin at 0,0,0, where it calculates the operation points' positions.

This point also aids in defining the stock material position and prevents the tool from machining outside the stock limitations. If you do not have a consistent 0,0,0 origin, you may cut stock materials differently, resulting in products that are not machined to specs. If you plan to machine multiple parts using the same program, you must replace the stock material once each part is finished and restock for the next part.

This is also true when multiple operators work on the same machine and application. For example, if this 0,0,0 is defined far outside the stock part, resulting in huge interpolation values on the CNC codes, you will obtain fault in the program or a decrease in precision. For example, attempting to represent a big geometry in CAD software could result in flaws and errors. The same is true for CNC machines.

To address this issue, CNC machines employ a technology similar to CAD: local coordinate systems known as "Work Coordinate Systems" or WCS, which can be defined for each CNC code or program. These WCS are reference points chosen when G-code is created that do not necessarily match the CAD model's 0,0,0.

Typically, the WCS position is on an edge or a physical feature that can be identified. The point must be easily duplicated, allowing the machine to return to the same location within a tight tolerance regardless of the machining motion.

### **3. Select CNC process.**

When you start a CNC machine, it doesn't inform you where the coordinates are, therefore the "Home" location is useful. By pressing the "home" button, the operator restarts and moves all three axes to their limits -X, +Y, +Z, which moves the table to the set home location, usually in the rear left corner. Then you have a recognized starting point for the subsequent procedures.

CNC machines can typically position each axis with an accuracy of +/-0.0002 inches, thanks to closed-loop servo systems. The CNC machine control provides a motion signal to a servo motor coupled to each machine axis through a controller board. The servo motor turns a ball screw attached to the table and moves it as needed. The axis position is continually monitored and compared to the planned position, with compensatory feedback provided.

### **4. Select and configure cutting tool and machining parameters.**

Before the software leaves the computer, measurement tools allow you to know the actual dimensions of the final machined product (as opposed to the design model, which might be significantly different). Wall thickness, volumes, depths, gaps, distances, angles, hole sizes, corner radii, scallop heights, and edges may all be checked. In the tool length offset page, enter the diameter of each tool. This will come in handy when you use Cutter Radius Compensation in your software.

### **5. Review driving CAD geometry.**

The CNC machining process includes CAD (computer-aided design) and CAM (computer-aided manufacturing). Several CAD software products have CAM features or provide plugins to link to machining applications. You may generate geometry, perform simulations, and forecast mistakes that would cost money during an actual machining process using 3D modeling. With practice, you may simulate CNC milling to optimize a wide range of machining process parameters such as machining time, material waste, and, at a higher level, tool wear, heat impacts, material characteristics, and others.

### **6. Transfer G-code program to CNC machine.**

### **7. Post Process and calibration.**

Make sure the workspace is free of any stray tools or equipment and that all safety switches are operational before turning on the machine.

Turn on the machine and take control.

To avoid accidentally knocking into the spindle while working, move it out of the way and remove any tools.

To guarantee that there are no chips or debris between the machine table and the vise, clean the machine table and the bottom of the vise.

Jog the device to locate it, then set the TLO (Tool Length Offsets). Set the fixture offset to locate the component XY datum once the vise or other fixture is correctly placed and positioned on the machine. Set the Z offset of the fixture.

Locate the vise such that the tool may reach all features on the component without exceeding the machine travel restrictions. Overrun should be included for lead-in/out moves. Before adding bolts, jog the machine to ensure that the vise does not come into touch with any machine sheet metal throughout its passage.

## **8. Verify toolpath.**

Following correct setup and simulation, post-processing occurs, in which the CAM software translates the simulated tool paths to CNC code. Users may zoom in on detail sections, cross-section the model, and see it in translucent mode to inspect places that would otherwise be impossible to see, such as the junction of drilled holes.

## **9. Set up and operate CNC machine to make part.**

## Vector graphics

Inkscape is open source, and various user-created extensions enhance the already formidable vector software's capabilities. As previously stated, one possible extension will generate a G-code file, but it is restricted to a 2D object.

Inkscape is not a native 3D authoring application; you must import it into a 3D modeling program to convert it into a 3D object. 3D printers require G-code instructions. Inkscape saves SVG files. Inkscape does have a plug-in for generating G-code for machines that are 2D cutters or plotters. However, converting the 2D Inkscape-produced SVG file to a 3D-printer-ready G-code file would require many steps.

When loading the program into mach3, there sometimes is an error caused by "special characters." These may not be visible in word pad since most are blank spaces The answer was to either eliminate the spaces following the error lines or copy and paste the entire program into a new text document. The situation is comparable to other puzzling technological issues.

When generating G-code this way, it is essential to know what kind of machine will process the G-code and how it interprets the code. This method is not recommended when operating CNC mills, lathes, and cutters since it is too dangerous.

For those machines, we recommend using more professional software, such as anything from Vectric. However, in these "do it yourself" projects, Inkscape serves quick an easy

## Feed rate calculation

In this project, the spindle is adjusted to have the constant RPM at 1500. The cutting speed (IPR) is rounded up to get 0.0333. Together we have both the feed forward and feed downward equal to

$$1500 \times 0.0333 = 50$$


Therefore, we set the feed and penetration feed in these example as 50.

## Locate Constrained Inscribed Circle

Finds the largest/smallest circle that fits entirely inside/outside the data points, subject to the additional restriction that the location in the X direction is fixed.

The greatest location restricted gage or the smallest ring gage pin that will fit inside a hole. This can happen if the hole is a tertiary datum feature.

Most of the time, there are two places of contact when the deviation is zero.

Increasing or decreasing the circle size reduces the space between the circle and the surface as well as the average deviation.  Vietnamese-German University

The average absolute deviation is minimized, with the restrictions that the minimal deviation is zero and the circle's X position is set at zero.

Because the Maximum Inscribed method is based on the most extreme "low"/"high" data values, it is vulnerable to outliers.

## G01 – Linear Interpolation Accuracy

When cutting in a straight line, use the G01 command. Before it can be executed, this command must have a feed rate (F) set. G01 X-100 F50.0 is an example of a typical block. As long as there is no additional movement, you do not need to include this instruction on every line. To make G-Code active, for example, just add it after a G02, G03, or G00 instruction. Similarly, a feed rate (F50) is only required once until you wish to adjust the pace at which you cut.

```
G00 X101 Z1.0;
```

```
G01 X100 Z-20 F100;
```

```
X110 Y-40;
```

```
G00 Z300;
```

This command can be used to cut all axes simultaneously or only one. It is uncommon to cut using the Z axis in addition to the X and Y axes, although it is doable if necessary.

When programming a profile, it is easy to utilize cutter compensation G41 and G42 since you don't have to account for the cutter's radius when calculating your tool paths; simply use the dimensions on the design and the machine will offset the cutter to obtain the proper dimensions.

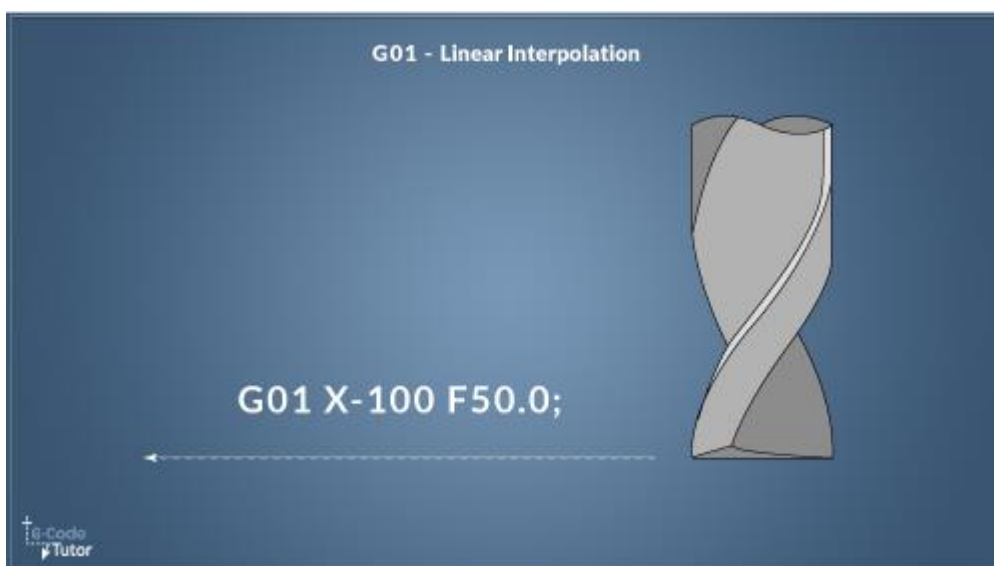


Figure 5.1: Sample Linear experiment

## Maximum Inscribed

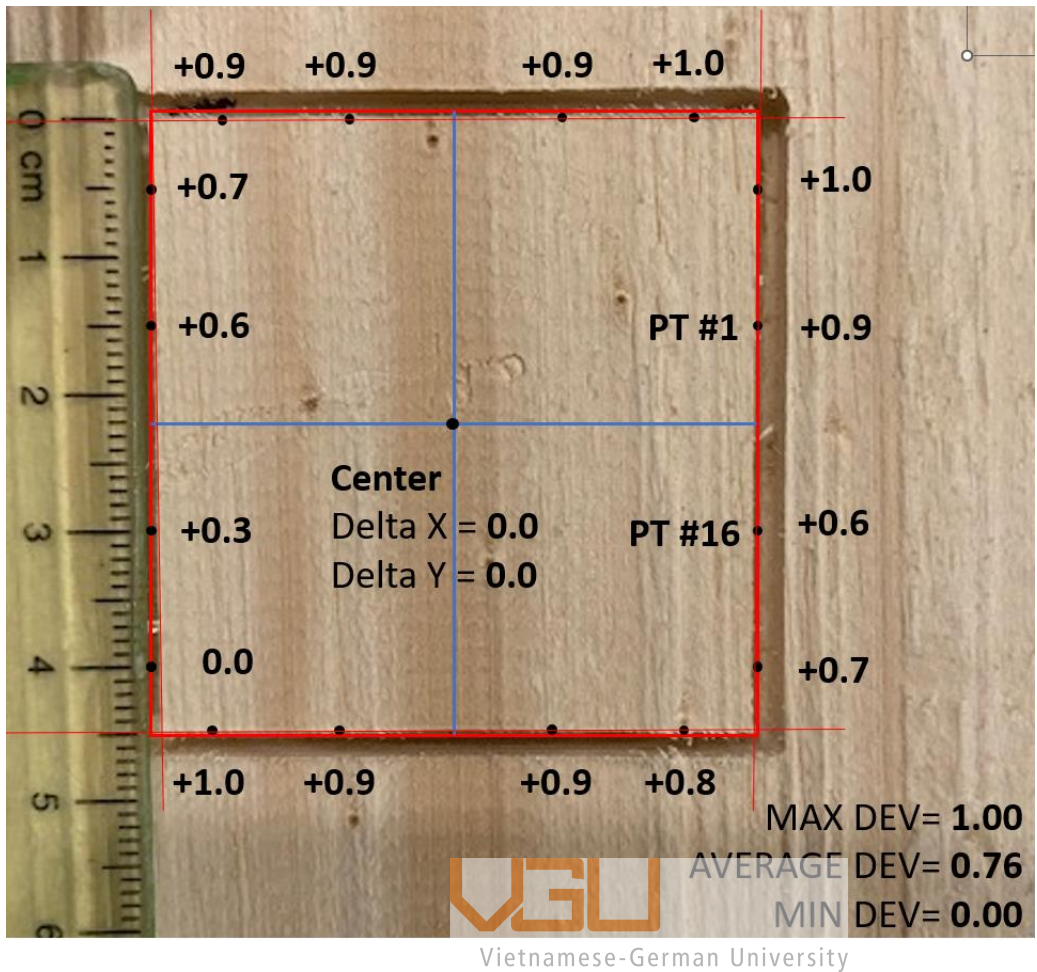


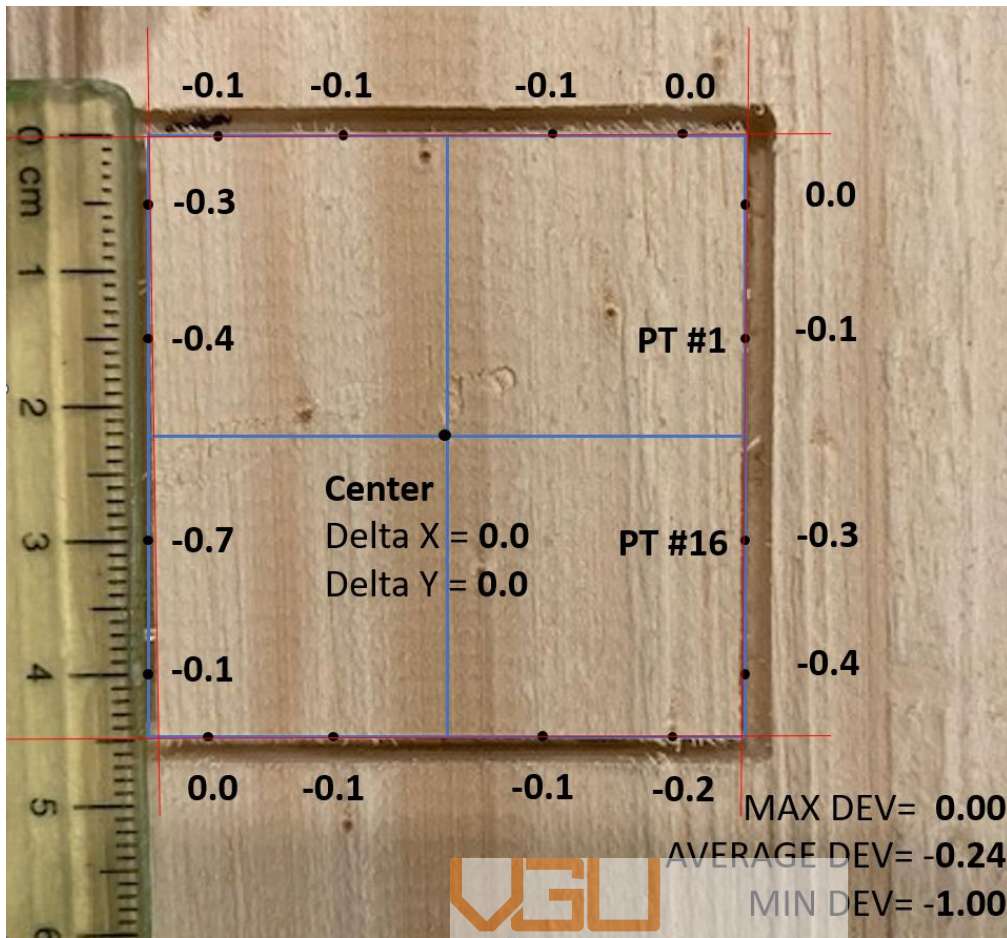
Figure 5.2: G01 - Linear Interpolation Accuracy checking Maximum Inscribed

Point	X	Y	Deviation	Deviation Squared
1	22.5	7.0	0.9	0.9
2	22.6	17.0	1.0	1.0
3	17.0	22.6	1.0	1.0
4	7.0	22.5	0.9	0.9
5	-7.0	22.5	0.9	0.9
6	-17.0	22.5	0.9	0.9
7	-22.3	17.0	0.7	0.8
8	-22.2	7.0	0.6	0.8
9	-21.9	-7.0	0.3	0.5
10	-21.6	-17.0	0.0	0.0
11	-17.0	-22.6	1.0	1.0
12	-7.0	-22.5	0.9	0.9
13	7.0	-22.5	0.9	0.9
14	17.0	-22.4	0.8	0.9
15	22.2	-17.0	0.7	0.8
16	22.3	-7.0	0.6	0.8
Avg			0.76	
Sum			12.1	13.4

Table 5.1: G01 - Linear Interpolation Accuracy checking Maximum Inscribed



## Minimum Inscribed



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Figure 5.3: G01 - Linear Interpolation Accuracy checking Minimum Inscribed

Point	X	Y	Deviation	Deviation Squared
1	22.5	7.0	-0.1	0.3
2	22.6	17.0	0.0	0.0
3	17.0	22.6	0.0	0.0
4	7.0	22.5	-0.1	0.3
5	-7.0	22.5	-0.1	0.3
6	-17.0	22.5	-0.1	0.3
7	-22.3	17.0	-0.3	0.5
8	-22.2	7.0	-0.4	0.6
9	-21.9	-7.0	-0.7	0.8
10	-21.6	-17.0	-1.0	1.0
11	-17.0	-22.6	0.0	0.0
12	-7.0	-22.5	-0.1	0.3
13	7.0	-22.5	-0.1	0.3
14	17.0	-22.4	-0.2	0.4
15	22.2	-17.0	-0.3	0.5
16	22.3	-7.0	-0.4	0.6
Avg			-0.24	
Sum			-3.9	6.5

Table 5.2: G01 - Linear Interpolation Accuracy checking Minimum Circumscribed



## G02 and G03 – Circular Interpolation Accuracy

G02 is used to manufacture an arc or radius clockwise, whereas G03 is used for anti-clockwise.

The G02/G03 command moves the cutter along a straight line with the given radius at the conclusion of this move, using a 'R' value to specify the radius.

If a feed rate is currently active, there is no need to add it to this line unless you want to modify the arc's feed rate.

```
G03 Y50.0 R10.0 F100.0;
```

The arc's center point can alternatively be determined using I, J, and K variables. The auxiliary axis is defined by I (X), J (Y), and K (Z). Using the preceding illustration, programming an arc with I and J values might look like this:

```
G03 Y50.0 I10.0 J40.0 F100.0;
```

The K is rarely utilized, however it is accessible if an arc along the Z axis is required.



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Any form may be machined by combining G02 with G01 and G03 (counterclockwise arc). These three G Codes form the core of G Code programming and will be used for cutting material.

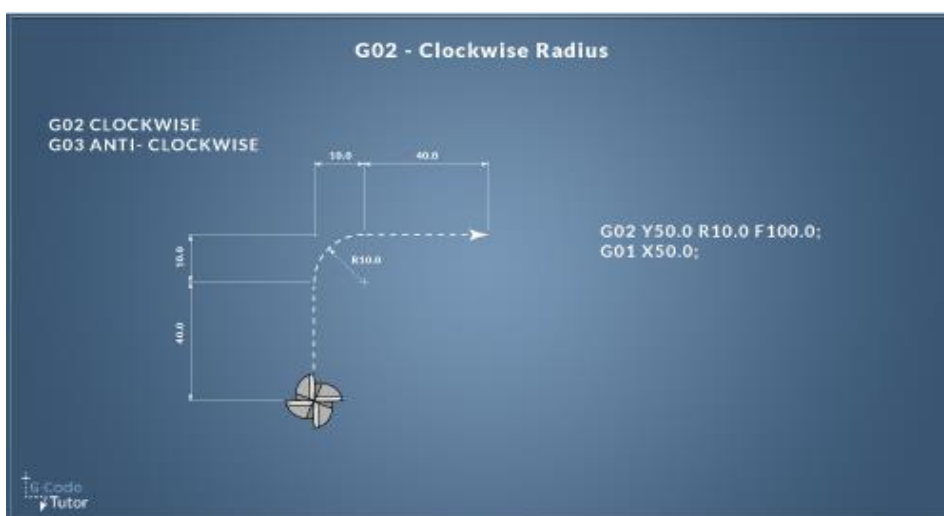


Figure 5.4: Sample of A clockwise G02 movement and G01

## Maximum Inscribed

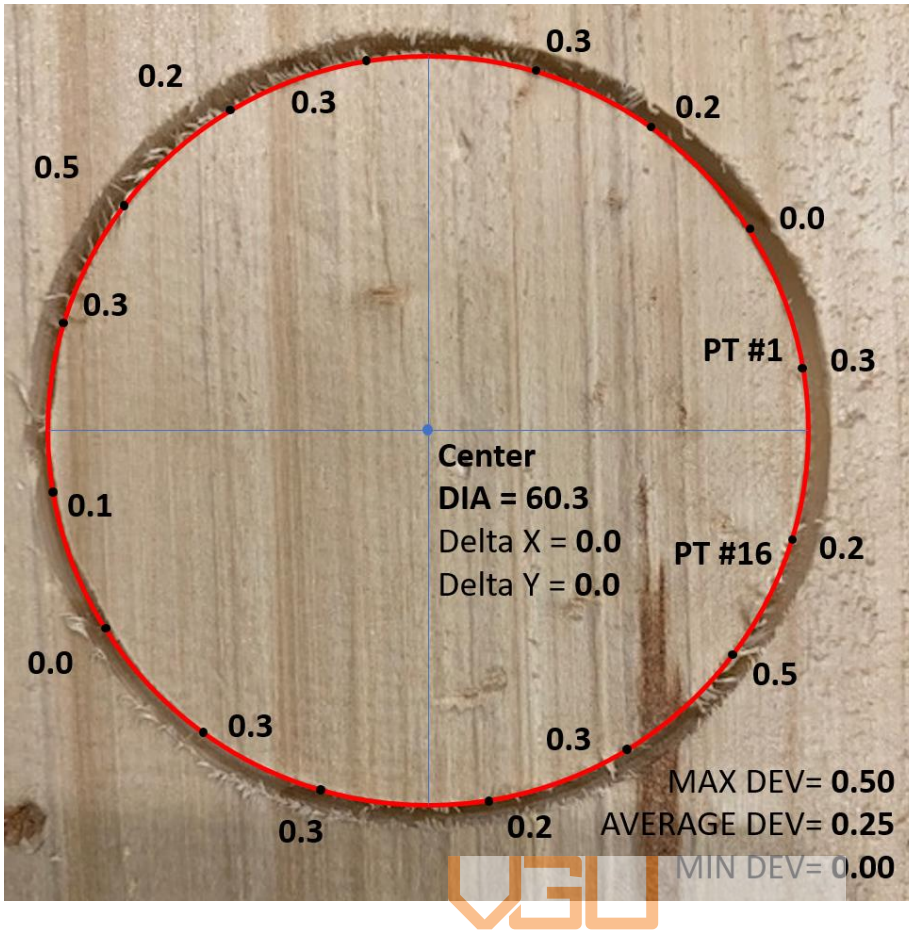


Figure 5.5: G02 and G03 - Circular Interpolation Accuracy checking - Maximum Inscribed

Point	Deviation	Deviation Squared
1	0.3	0.5
2	0.0	0.0
3	0.2	0.4
4	0.3	0.5
5	0.3	0.5
6	0.2	0.4
7	0.5	0.7
8	0.3	0.5
9	0.1	0.3
10	0.0	0.0
11	0.3	0.5
12	0.3	0.5
13	0.2	0.4
14	0.3	0.5
15	0.5	0.7
16	0.2	0.4
Avg	0.25	
Sum	4.0	7.4

Table 5.3: G02 and G03 - Circular Interpolation Accuracy checking - Maximum Inscribed

## Minimum Inscribed

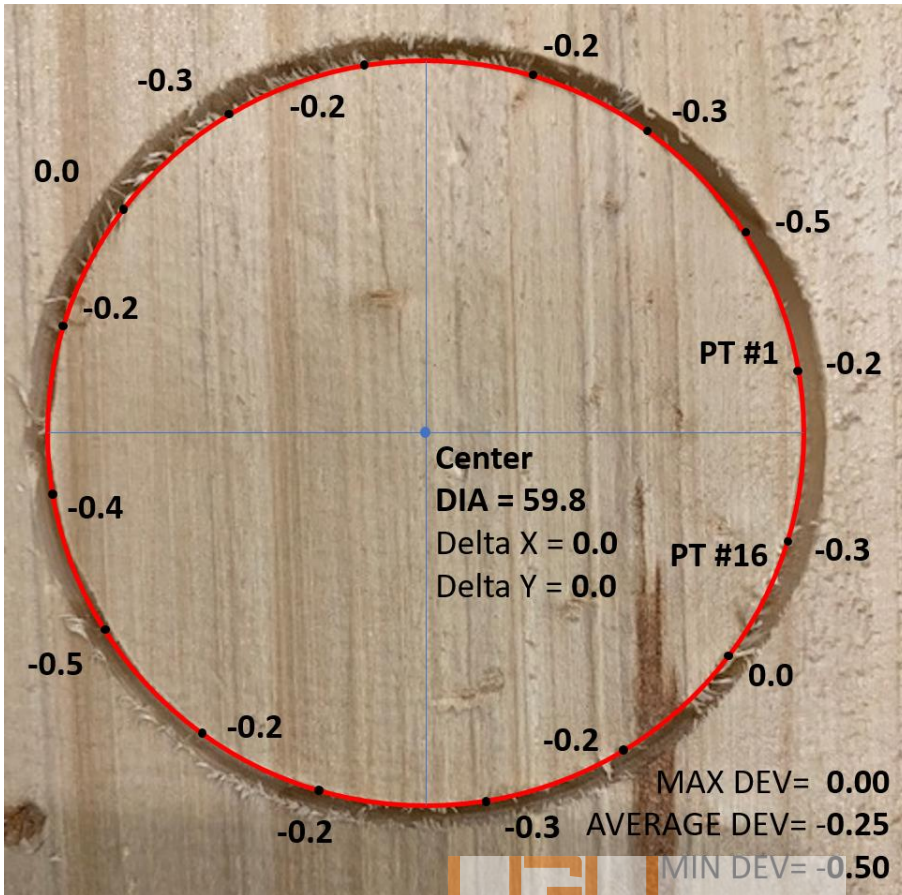


Figure 5.6: G02 and G03 - Circular Interpolation Accuracy checking - Minimum Circumscribed

Point	Deviation	Deviation Squared
1	-0.2	0.4
2	-0.5	0.7
3	-0.3	0.5
4	-0.2	0.4
5	-0.2	0.4
6	-0.3	0.5
7	0.0	0.0
8	-0.2	0.4
9	-0.4	0.6
10	-0.5	0.7
11	-0.2	0.4
12	-0.2	0.4
13	-0.3	0.5
14	-0.2	0.4
15	0.0	0.0
16	-0.3	0.5
Avg	-0.25	
Sum	-4.0	7.4

Table 5.4: G02 and G03 - Circular Interpolation Accuracy checking - Minimum Circumscribed

### **3D milling samples**

We not yet being able to generate the G code for 3d Milling at the moment. The machine is able to move all three axes at a time, proving the ability to milling 3d models. We will focus on the software that allow us to generate G code later on as the samples found online is not really compatible with the mach3 itself and also the calibration of the coordinates.



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

### **Conclusion**

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

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

### **Future works**

We aim to focus on the software that helps with generation G code for the 3d model to ensure the ability of our prototype. Further, we 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 our focuses. Configuring the drive will enable us to work in many driving modes and speeds.



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## Appendix

### G code for Spiral sample

%

(Header)

(Generated by gcodetools from Inkscape.)

(Using default header. To add your own header create file "header" in the output dir.)

M3

(Header end.)

G21 (All units in mm)

(Start cutting path id: path4134)



(Change tool to Cylindrical cutter)/vietnamese-German University

G00 Z7.000000

G00 X0.153346 Y0.154485

G01 Z-0.500000 F50.0(Penetrate)

G02 X0.048995 Y-0.493197 Z-0.500000 I-0.284694 J-0.286379 F50.000000

G02 X-0.566627 Y-0.569750 Z-0.500000 I-0.416275 J0.833972

G02 X-1.471388 Y0.357271 Z-0.500000 I0.251989 J1.150966

G02 X-1.295123 Y1.594431 Z-0.500000 I1.877970 J0.363572

G02 X0.364065 Y2.764521 Z-0.500000 I1.947084 J-0.999555  
G02 X2.313264 Y2.327188 Z-0.500000 I0.380420 J-2.866932  
G02 X3.768566 Y-0.056375 Z-0.500000 I-1.743892 J-2.700800  
G02 X3.050283 Y-2.725407 Z-0.500000 I-3.886097 J-0.385351  
G02 X-0.055828 Y-4.472995 Z-0.500000 I-3.439901 J2.479828  
G02 X-3.446519 Y-3.466687 Z-0.500000 I-0.387637 J4.909396  
G02 X-5.489641 Y0.361325 Z-0.500000 I3.210597 J4.172833  
G02 X-4.192061 Y4.474322 Z-0.500000 I5.933045 J0.389406  
G02 X0.357568 Y6.814731 Z-0.500000 I4.902694 J-3.938251  
G02 X5.193156 Y5.224126 Z-0.500000 I0.391176 J-6.956409  
G02 X7.831905 Y-0.046974 Z-0.500000 I-4.663932 J-5.630834  
G02 X5.947221 Y-5.605298 Z-0.500000 I-7.979423 J-0.393071  
G02 X-0.045268 Y-8.543068 Z-0.500000 I-6.357925 J5.388302  
G02 X-6.326410 Y-6.363626 Z-0.500000 I-0.395108 J9.002132  
G02 X-9.563667 Y0.350204 Z-0.500000 I6.111759 J7.084333  
G02 X-7.088999 Y7.354214 Z-0.500000 I10.024593 J0.397276  
G02 X0.346138 Y10.891291 Z-0.500000 I7.810271 J-6.834555  
G02 X8.073047 Y8.121064 Z-0.500000 I0.399557 J-11.046859  
G02 X11.910191 Y-0.035360 Z-0.500000 I-7.556862 J-8.535876  
G02 X8.844159 Y-8.485190 Z-0.500000 I-12.068970 J-0.401931  
G00 Z7.000000





(End cutting path id: path4134)

(Footer)

M5

G00 X0.0000 Y0.0000

M2

(Using default footer. To add your own footer create file "footer" in the output dir.)

(end)

%



## G code for Circle filling sample

%

(Header)

(Generated by gcodetools from Inkscape.)

(Using default header. To add your own header create file "header" in the output dir.)

M3

(Header end.)

G21 (All units in mm)

(Start cutting path id: path8467)

(Change tool to Cylindrical cutter)



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G00 Z7.000000

G00 X0.079785 Y0.679808

G01 Z-0.500000 F50.0(Penetrate)

G01 X0.096312 Y0.620521 Z-0.500000 F50.000000

G03 X-0.250293 Y0.005980 Z-0.500000 I0.371498 J-0.614541

G03 X-0.149450 Y-0.427834 Z-0.500000 I0.983526 J0.000000

G03 X-0.025684 Y-0.597536 Z-0.500000 I0.546513 J0.268596

G01 X0.079785 Y-0.667846 Z-0.500000

G01 X0.183301 Y-0.597536 Z-0.500000

G03 X0.307785 Y-0.427821 Z-0.500000 I-0.430224 J0.446075

G03 X0.409863 Y0.005980 Z-0.500000 I-0.870722 J0.433801

G03 X0.307923 Y0.439531 Z-0.500000 I-0.972916 J-0.000000

G03 X0.183301 Y0.609495 Z-0.500000 I-0.554982 J-0.276257

G01 X0.079785 Y0.679805 Z-0.500000

G01 X0.079785 Y0.679808 Z-0.500000

G00 Z7.000000

(End cutting path id: path8467)



(Start cutting path id: path8463)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y0.632933

G01 Z-0.500000 F50.0(Penetrate)

G03 X-0.438622 Y0.525190 Z-0.500000 I-0.000000 J-1.301037 F50.000000

G03 X-0.719043 Y0.338011 Z-0.500000 I0.377805 J-0.869649

G03 X-0.870914 Y0.111091 Z-0.500000 I0.446965 J-0.463422  
G03 X-0.890918 Y0.005980 Z-0.500000 I0.266147 J-0.105111  
G03 X-0.870847 Y-0.099346 Z-0.500000 I0.286399 J-0.000000  
G03 X-0.719043 Y-0.326052 Z-0.500000 I0.598895 J0.236848  
G03 X-0.438664 Y-0.513214 Z-0.500000 I0.658180 J0.682399  
G03 X0.079785 Y-0.620973 Z-0.500000 I0.518445 J1.193274  
G03 X0.926957 Y-0.279659 Z-0.500000 I0.000000 J1.222038  
G03 X1.048535 Y0.005980 Z-0.500000 I-0.274758 J0.285639  
G03 X1.028328 Y0.111410 Z-0.500000 I-0.285141 J0.000000  
G03 X0.876660 Y0.338011 Z-0.500000 I-0.604561 J-0.240586  
G03 X0.596676 Y0.525158 Z-0.500000 I-0.659848 J-0.684166  
G03 X0.079785 Y0.632933 Z-0.500000 I-0.516891 J-1.185618  
G01 X0.079785 Y0.632933 Z-0.500000  
G00 Z7.000000

(End cutting path id: path8463)

(Start cutting path id: path8465)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y0.580198

G01 Z-0.500000 F50.0(Penetrate)

G01 X0.105553 Y0.498557 Z-0.500000 F50.000000

G03 X-0.150684 Y0.005980 Z-0.500000 I0.345335 J-0.492577

G03 X-0.055996 Y-0.389237 Z-0.500000 I0.872140 J0.000000

G03 X0.044629 Y-0.525270 Z-0.500000 I0.454844 J0.231219

G02 X0.082419 Y-0.561727 Z-0.500000 I-188.495539 J-195.421742

G01 X0.079789 Y-0.568240 Z-0.500000

G01 X0.077164 Y-0.561745 Z-0.500000

G02 X0.114949 Y-0.525270 Z-0.500000 I45.213705 J-46.800182

G03 X0.214962 Y-0.389163 Z-0.500000 I-0.347035 J0.359805

G03 X0.308308 Y0.005980 Z-0.500000 I-0.789670 J0.395143

G03 X0.215103 Y0.400878 Z-0.500000 I-0.883169 J0.000000

G03 X0.114949 Y0.537230 Z-0.500000 I-0.447335 J-0.223620

G02 X0.077163 Y0.573703 Z-0.500000 I50.519719 J52.376106

G01 X0.079789 Y0.580200 Z-0.500000

G01 X0.079785 Y0.580198 Z-0.500000

G00 Z7.000000

(End cutting path id: path8465)

(Start cutting path id: path8461)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y1.832151

G01 Z-0.500000 F50.0(Penetrate)

G03 X-0.877400 Y1.643214 Z-0.500000 I0.000000 J-2.519092 F50.000000

G03 X-1.551074 Y1.203245 Z-0.500000 I0.814600 J-1.983049

G03 X-1.975859 Y0.580001 Z-0.500000 I1.284686 J-1.331987

G03 X-2.090137 Y0.005980 Z-0.500000 I1.384524 J-0.574021

G03 X-1.975614 Y-0.567326 Z-0.500000 I1.492260 J-0.000000

G03 X-1.551074 Y-1.189333 Z-0.500000 I1.711206 J0.712070

G02 X-1.551074 Y-1.190333 Z-0.500000 I-7.500749 J-0.000945

G02 X-1.551074 Y-1.191333 Z-0.500000 I-7.500749 J-0.000055

G03 X-0.877432 Y-1.631292 Z-0.500000 I1.488203 J1.542955

G03 X0.079785 Y-1.820239 Z-0.500000 I0.957217 J2.330187

G03 X1.781614 Y-1.118715 Z-0.500000 I-0.000000 J2.414999

G03 X2.249707 Y0.005933 Z-0.500000 I-1.117004 J1.124648

G03 X2.135436 Y0.579930 Z-0.500000 I-1.498769 J-0.000000

G03 X1.710645 Y1.203198 Z-0.500000 I-1.709552 J-0.708760

G03 X1.036769 Y1.643250 Z-0.500000 I-1.488370 J-1.543224



G03 X0.079785 Y1.832104 Z-0.500000 I-0.956980 J-2.330229

G01 X0.079785 Y1.832151 Z-0.500000

G00 Z7.000000

(End cutting path id: path8461)

(Start cutting path id: path8459)

(Change tool to Cylindrical cutter)

G00 Z7.000000



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G00 X0.079785 Y3.033323

G01 Z-0.500000 F50.0(Penetrate)

G03 X-1.318997 Y2.759928 Z-0.500000 I-0.000000 J-3.715012 F50.000000

G03 X-2.385058 Y2.066527 Z-0.500000 I1.263492 J-3.108743

G03 X-3.078943 Y1.055351 Z-0.500000 I2.121095 J-2.199193

G03 X-3.291308 Y0.005980 Z-0.500000 I2.486461 J-1.049371

G03 X-3.078869 Y-1.043583 Z-0.500000 I2.698916 J-0.000000

G03 X-2.385058 Y-2.054567 Z-0.500000 I2.814777 J1.188141

G03 X-1.318994 Y-2.746978 Z-0.500000 I2.320531 J2.405897



G03 X0.079785 Y-3.019411 Z-0.500000 I1.398779 J3.454734

G03 X2.616876 Y-1.980340 Z-0.500000 I-0.000000 J3.616932

G03 X3.448926 Y0.005980 Z-0.500000 I-1.954906 J1.986320

G03 X3.236563 Y1.055332 Z-0.500000 I-2.698772 J-0.000000

G03 X2.542676 Y2.066527 Z-0.500000 I-2.815126 J-1.188082

G03 X1.477302 Y2.759831 Z-0.500000 I-2.331316 J-2.417235

G03 X0.079785 Y3.033323 Z-0.500000 I-1.397517 J-3.433830

G01 X0.079785 Y3.033323 Z-0.500000

G00 Z7.000000

(End cutting path id: path8459)



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(Start cutting path id: path8457)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y4.232542

G01 Z-0.500000 F50.0(Penetrate)

G03 X-1.759841 Y3.875221 Z-0.500000 I-0.000000 J-4.914208 F50.000000

G03 X-3.217090 Y2.929808 Z-0.500000 I1.705490 J-4.224623  
G03 X-4.179501 Y1.531614 Z-0.500000 I2.956495 J-3.065352  
G03 X-4.490527 Y0.005980 Z-0.500000 I3.586233 J-1.525634  
G03 X-4.180298 Y-1.519799 Z-0.500000 I3.907188 J0.000000  
G03 X-3.219043 Y-2.917849 Z-0.500000 I3.908716 J1.658022  
G02 X-3.218068 Y-2.917849 Z-0.500000 I0.000985 J-5.100509  
G02 X-3.217093 Y-2.917849 Z-0.500000 I-0.000009 J-5.100509  
G03 X-1.759860 Y-3.863264 Z-0.500000 I3.162590 J3.278944  
G03 X0.079782 Y-4.220583 Z-0.500000 I1.839642 J4.556997  
G03 X3.447720 Y-2.847325 Z-0.500000 I0.000000 J4.816593  
G03 X4.648142 Y0.005980 Z-0.500000 I-2.790828 J2.853305  
G03 X4.337978 Y1.531572 Z-0.500000 I-3.907016 J-0.000000  
G03 X3.376657 Y2.929808 Z-0.500000 I-3.909154 J-1.658054  
G03 X1.919271 Y3.875272 Z-0.500000 I-3.162855 J-3.279408  
G03 X0.079785 Y4.232542 Z-0.500000 I-1.839486 J-4.556866  
G01 X0.079785 Y4.232542 Z-0.500000  
G00 Z7.000000

(End cutting path id: path8457)

(Start cutting path id: path8455)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y5.431761

G01 Z-0.500000 F50.0(Penetrate)

G03 X-2.201912 Y4.990559 Z-0.500000 I0.000000 J-6.120558 F50.000000

G03 X-4.051074 Y3.793089 Z-0.500000 I2.144736 J-5.338447

G03 X-5.281819 Y2.008176 Z-0.500000 I3.791525 J-3.931129

G03 X-5.691699 Y0.005980 Z-0.500000 I4.685255 J-2.002196

G03 X-5.281761 Y-1.996374 Z-0.500000 I5.095249 J-0.000000

G03 X-4.051074 Y-3.781130 Z-0.500000 I5.021965 J2.146229

G03 X-2.201920 Y-4.978608 Z-0.500000 I3.993711 J4.140640

G03 X0.079785 Y-5.419802 Z-0.500000 I2.281705 J5.679501

G03 X4.277756 Y-3.714939 Z-0.500000 I0.000000 J6.020872

G03 X5.849316 Y0.005980 Z-0.500000 I-3.619157 J3.720919

G03 X5.439431 Y2.008169 Z-0.500000 I-5.095046 J-0.000000

G03 X4.208692 Y3.793089 Z-0.500000 I-5.022512 J-2.146356

G03 X2.360300 Y4.990434 Z-0.500000 I-3.995749 J-4.143011

G03 X0.079785 Y5.431761 Z-0.500000 I-2.280515 J-5.671514



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G01 X0.079785 Y5.431761 Z-0.500000

G00 Z7.000000

(End cutting path id: path8455)

(Start cutting path id: path8453)

(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y6.632933



G01 Z-0.500000 F50.0(Penetrate)

G03 X-2.644047 Y6.107794 Z-0.500000 I-0.000000 J-7.326663 F50.000000

G03 X-4.885058 Y4.658323 Z-0.500000 I2.583870 J-6.452033

G03 X-6.383147 Y2.485868 Z-0.500000 I4.615745 J-4.785697

G03 X-6.890918 Y0.005980 Z-0.500000 I5.801846 J-2.479888

G03 X-6.382931 Y-2.473020 Z-0.500000 I6.302809 J-0.000000

G03 X-4.885058 Y-4.644411 Z-0.500000 I6.115153 J2.616037

G03 X-2.644074 Y-6.094918 Z-0.500000 I4.833709 J5.011543

G03 X0.079785 Y-6.620973 Z-0.500000 I2.723855 J6.788878

G03 X5.105816 Y-4.584180 Z-0.500000 I-0.000000 J7.219564

G03 X7.048535 Y0.005980 Z-0.500000 I-4.451342 J4.590160

G03 X6.540755 Y2.485868 Z-0.500000 I-6.309507 J0.000000

G03 X5.042676 Y4.658323 Z-0.500000 I-6.114121 J-2.613417

G03 X2.802468 Y6.107657 Z-0.500000 I-4.826763 J-5.004650

G03 X0.079785 Y6.632933 Z-0.500000 I-2.722683 J-6.793650

G01 X0.079785 Y6.632933 Z-0.500000

G00 Z7.000000

(End cutting path id: path8453)

(Start cutting path id: path8451)



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(Change tool to Cylindrical cutter)

G00 Z7.000000

G00 X0.079785 Y7.832152

G01 Z-0.500000 F50.0(Penetrate)

G03 X-3.085162 Y7.222880 Z-0.500000 I-0.000000 J-8.525019 F50.000000

G03 X-5.717090 Y5.521605 Z-0.500000 I3.025543 J-7.567087

G03 X-7.483381 Y2.962640 Z-0.500000 I5.450525 J-5.651213

G03 X-8.090137 Y0.005980 Z-0.500000 I6.900374 J-2.956660

G03 X-7.483341 Y-2.950802 Z-0.500000 I7.507276 J0.000000  
G03 X-5.717090 Y-5.509645 Z-0.500000 I7.216414 J3.092156  
G03 X-3.085155 Y-7.210938 Z-0.500000 I5.657204 J5.865332  
G03 X0.079785 Y-7.820192 Z-0.500000 I3.164940 J7.915962  
G03 X5.934363 Y-5.452881 Z-0.500000 I-0.000000 J8.423110  
G03 X8.249707 Y0.005980 Z-0.500000 I-5.277475 J5.458861  
G03 X7.642046 Y2.962677 Z-0.500000 I-7.497038 J-0.000000  
G03 X5.874707 Y5.521605 Z-0.500000 I-7.226986 J-3.101588  
G03 X3.243613 Y7.222731 Z-0.500000 I-5.659391 J-5.867965  
G03 X0.079785 Y7.832152 Z-0.500000 I-3.163828 J-7.907845  
G01 X0.079785 Y7.832152 Z-0.500000  
G00 Z7.000000



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(End cutting path id: path8451)

(Footer)

M5

G00 X0.0000 Y0.0000

M2

(Using default footer. To add your own footer create file "footer" in the output dir.)

(end)

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Page: 3

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