

PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH



UNIVERSITY SAAD DAHLAB DE BLIDA 1
FACULTY OF TECHNOLOGY
DEPARTMENT OF MECHANICS
LABORATORY OF STRUCTURE

Project Graduation
For Obtaining The Master's Degree In
Mechanical And Production Manufacturing

Applying Artificial Intelligence on a Numerical Controlled
Machine

Proposed and supervised by:
Temmar Mustapha
Ait Saadi Houcine

Realized by:
Benahmed Abderrahim
Benachour Sohaib

College year 2018/2019

Acknowledgment

We would love to take these few lines,
to thank our parents for their unconditional support and encouragements throughout our entire
academic and professional life.

For all the care and the supervision they raised us with. None of this would have been
possible if it wasn't for their great efforts.

As well as our promoters and teachers for this year and our previous years, for their unlimited
help and guidance.

Our friends also deserve a share of our gratitude for the joy they offered in the hard times and
all the aid they provided along with the wise advices.

ملخص:

تُعرف آلات التحكم العددي بالكمبيوتر بأنها عملية تصنيع متقدمة تستخدم بشكل متزايد في الصناعة الحديثة. في الواقع ، الذكاء الاصطناعي له تأثير كبير على أداء الآلات الصناعية. توضح أطروحة الماستر هذه مرونة منهج الشبكة العصبية الاصطناعية في أجهزة التحكم العددي بالكمبيوتر، من خلال التنبؤ بالأخطاء قبل حدوثها ، إما عن طريق إيقاف أو تقليل سرعة الجهاز. المعاملات التي تؤخذ في عين الاعتبار هي ، تيار محركات خطوة خطوة وخطوات المشفر التي فقدت.

كلمات المفاتيح: التحكم العددي بالكمبيوتر; الذكاء الاصطناعي; الشبكة العصبية الاصطناعية.

Résumé :

L'usinage du CNC est connu en tant qu'un processus avancé de plus en plus utilisé dans l'industrie moderne. En réalité, l'intelligence artificielle a un impact important sur les performances des machines industrielles. Ce mémoire de master décrit la flexibilité de l'approche de réseau de neurone artificiel dans les machines CNC, en prévoyant les erreurs avant qu'elles ne se produisent, soit en arrêtant, soit en réduisant la vitesse de la machine. Les paramètres pris en compte sont le courant des moteurs pas à pas et les pas perdus du encodeur.

Mots clés : CNC; l'intelligence artificielle; réseau de neurones artificiels.

Abstract :

CNC machining is known as an advanced machining process increasingly used for modern industry. Actually, Artificial Intelligence has a great impact on industrial machines performances. This master's dissertation outlines the flexibility of Artificial Neural Network approach in CNC machines, by predicting errors before happening, either by stopping or reducing the speed of the machine. The parameters taken into account are, stepper motors current and encoder lost steps.

Keywords : CNC; Artificial Intelligence; Artificial Neural Network.

List of abbreviations and symbols

e_{ij}	element of the error vector.
o_i	output vector.
δ_j^{out}	local gradient of neuron j .
Δw	small change applied to weight w .
μ	momentum.
3D	3 Dimensions.
AI	Artificial Intelligence.
AM	Automatic Machining.
ANN	Artificial Neural Network.
API	Application Programming Interface.
ATC	Automatic Tool Changer.
b_k	the bias.
CALS	Computer-aided Acquisition and Logistic Support.
CAM	Computer-Aided Manufacturing.
CMM	Coordinate Measuring Machine.
CNC	Computer Numerical Control.
CSV	Comma-Separated Values.
DC	Direct Current.
d_i	output vector.
DIY	Do It Yourself.
EDM	Electrical Discharge Machining.
EM	Electromagnetic.
EMC	Enhanced Machine Controller.
EMF	Back Electromotive Force.
EPROM	Erasable Programmable Read Only Memory.
F	activation function.
FEA	Finite Element Analysis.
FEM	Finite Element Method.
FPS	Frame Per Second.
FU	Function Unit.
G-Code	Geometric Code.
HOAM	Hierarchical Open Architecture Multi-processor.
HP	Horse power.
i	synapse.
IBM	International Business Machines.
IC	Integrated Circuits.
ICLP	Intelligent Closed Loop Processing.
IDE	Integrated Development Environment.
IR	Inner Ring.
IROD	Outer Diameter of the Inner Ring.
j	hidden neuron.
k	neuron.
Kg	Kilogram.
l	layer.
LED	Light Emitting Diode.
M	Metre.

M-Code	Machine Code.
MDF	Medium-Density Fibreboard.
MIT	Massachusetts Institute of Technology.
MLP	Multi-Layer Perceptron.
Mm	Millimetre.
MMI	Man Machine Interface.
Mpa	Mega Pascal.
N	Newton.
NC	Numerical Control.
NCMS	National Center for Manufacture Science.
NN	Neural Network.
OAC	Open Architecture Control.
OCR	Optical Character Recognition.
OD	Outer Ring.
OMAC	Open Modulate Architecture Controllers.
Op-codes	operation code.
OR	Outer Ring.
ORID	Inner Diameter of the Outer Ring.
OSACA	Open System Architecture for Controls within Automation Systems.
OSEC	Open System Environment for Controller.
PDP	Parallel Distributed Processing.
PLC	Programmable Logical Controllers.
PTFE	Polytetrafluoroethylene.
PWM	Pulse Width Modulation.
RAM	Random Access Memory.
RBF	Radial Basis Function.
Relu	Rectifier linear unit.
ROM	Read Only Memory.
S	some.
u_k	linear combiner output.
USA	United State of America.
v_k	activation potential.
VMC	Vertical Machining Center.
w_i	synaptic weight.
x_i	input signal.
y_k	output signal.
η	learning rate.
$\phi(\cdot)$	activation function.

List Of Content

General introduction

Chapter I Computer Numerical Control Machines

I.1	Introduction	1
I.2	Definition.....	1
I.3	History	2
I.3.1	Early MIT Research on Numerical Control.....	2
I.3.2	The First CNC Machine.....	3
I.4	Staples of CNC Technology	4
I.5	Area of use.....	4
I.5.1	Industries for removing metal.....	4
I.5.2	Industries for Fabricating Metals.....	5
I.5.3	Electrical Discharge Machining (EDM) Industry.....	5
I.5.4	Other Industries where CNC machines are used	5
I.6	Architecture types of CNC Machines.....	6
I.6.1	OSACA Architecture (Open System Architecture for Controls within Automation Systems)	6
I.6.2	OMAC Architecture (Open Modulate Architecture Controllers).....	8
I.6.3	HOAM-CNC Architecture (Hierarchical Open Architecture Multi-processor)	9
I.6.4	OSEC Architecture (Open System Environment for Controller)	10
I.7	CNC milling machine components	11
I.7.1	the Frame	11
I.7.2	Table	12
I.7.3	Spindle	12
I.7.4	Axes	12
I.7.5	CNC Controller.....	13
I.7.6	Motors.....	13
I.7.7	Power supply.....	13
I.7.8	G-code and M-code.....	13
7.8.1	Example of G-code and M-code commands	14
7.8.2	Some of the function commands	14
I.8	Software.....	16
I.8.1	GRBL software	17
I.9	Conclusion.....	18

Chapter II Artificial Neural Network

II.1	Introduction	19
II.2	Definition	19
II.3	Biological neural network	20
II.4	How artificial neural networks work?	22
II.5	Mathematical model of the neuron	23
II.6	Models of a neuron	25
II.7	Multi-layer perceptron	28
II.7.1	Input neurons	29
II.7.2	Output neurons.....	29
II.7.3	Hidden neurons	29
II.8	Back propagation network training algorithm	30
II.9	Application part	33
II.9.1	Application of Real-time OCR Neural Network.	33
II.9.2	Application of Neural Network in CNC Machine	37
II.10	Conclusion	39

Chapter III Electronics

III.1	Stepper motors	40
III.1.1	Definition of a stepper motor	40
III.1.2	Characteristics	42
1.2.1	Holding Torque	42
1.2.2	Open loop positioning	42
1.2.3	Load Independent	42
III.1.3	Types of Stepper Motors.....	42
1.3.1	Permanent Magnet Motor.....	42
1.3.2	Variable Reluctance.....	43
III.2	Motor driver	43
III.2.1	Unipolar drive circuit	43
III.2.2	Bipolar drive circuit	44
III.2.3	Micro-stepping	46
III.3	Arduino Board	46
III.3.1	Definition	46
III.3.2	Arduino board types.....	47
III.3.3	Arduino Uno R3.....	47
3.3.1	The brain ATmega328 microcontroller chip	48
3.3.2	Board details	49

3.3.3	Arduino IDE	50
III.4	Motion sensors (end stops)	51
III.4.1	Types of end-stops	51
4.1.1	Mechanical end-stop.....	51
4.1.2	Optical end-stop.....	52
4.1.3	Magnetic end-stop	53
III.5	Encoders.....	53
III.5.1	How encoders work ?.....	55
III.6	Router motor	56
III.6.1	Self-Contained Spindles.....	58
III.6.2	Fabricated Spindles	59
III.6.3	DIY CNC Spindle Selection	59
III.7	Application Part	60
III.7.1	Back EMF	60
III.7.2	Learning circuit.....	60
III.8	Conclusion.....	61

Chapter IV Mechanical Study

IV.1	Introduction	62
IV.2	Type of materials used in CNC machines	62
IV.2.1	CNC materials selection guidelines	63
IV.2.2	Summary table for metals	64
IV.2.3	Overview of common CNC metal alloys.....	64
2.3.1	Aluminium alloys	64
2.3.2	Stainless steel.....	66
IV.3	Machine structure	67
IV.3.1	Static Load	67
IV.3.2	Dynamic Load.....	68
IV.3.3	Thermal Load.....	68
IV.4	Guideways.....	69
IV.4.1	Types of guideways	69
4.1.1	Friction Guide ways	69
4.1.2	Anti-Friction Linear Motion Guide ways.....	70
IV.4.2	Different Shape of Guide Ways	70
4.2.1	V-Type Guide Ways:.....	70
4.2.2	Flat Type Guide Ways.....	71
4.2.3	Dove Tail Type Guideways.....	72

4.2.4	Cylindrical Type Guideways	72
IV.4.3	Anti-friction	73
4.3.1	Hydro-static Guide ways:	73
4.3.2	Aerostatic Guideways:.....	74
IV.5	Ball bearing.....	74
IV.5.1	Description	75
IV.6	Bushing bearing.....	75
IV.6.1	Standard Linear Bushing.....	75
IV.6.2	Aluminium Case Unit bushing bearing.....	76
IV.7	Lead screw	77
IV.7.1	Types of lead screws	77
IV.8	Timing belt	77
IV.9	Application Part	79
IV.9.1	Design	79
9.1.1	Working space	79
9.1.2	Size of the machine	80
IV.9.2	Machine parts.....	81
IV.9.3	Static study.....	82
9.3.1	Calculation for motor performance	82
9.3.2	SolidWorks software	83
9.3.3	Finite Element Analysis (FEA) or Finite Element Method (FEM)	84
9.3.4	Y axis study for Stress and for displacement	85
9.3.5	X axis study for Stress and for displacement	89
IV.9.4	Used materials.....	90
9.4.1	Type of wood.....	90
9.4.2	Type of metal rods.....	90
9.4.3	Type of support metal.....	91
IV.10	The final result.....	91
IV.11	Conclusion.....	91
	General conclusion	

List of figures

Figure I.1: Router CNC machine Badog class1	2
Figure I.2: first made CNC machine	3
Figure I.3: System platform (OSACA, 1998).....	7
Figure I.4: OMAC System simplified plant (Yen, 1998)	8
Figure I.5: HOAM-CNC Hardware global architecture	9
Figure I.6: Architecture OSEC	10
Figure I.7: Main frame of a DIY CNC machine.....	12
Figure I.8: GRBL Software desktop platform.	17
Figure II.1: Model of the biological neuron.	20
Figure II.2: Neural network multiple layers	22
Figure II.3: Nonlinear model of a neuron, labeled k	24
Figure II.4: Affine transformation produced by the presence of a bias	27
Figure II.5: Another nonlinear model of a neuron; accounts for the bias b_k	28
Figure II.6: Multi-layer perceptron.....	29
Figure II.7: Neural Network Library	33
Figure II.8: Detecting objects	34
Figure II.9: Progress of the training	35
Figure II.10: Model testing	35
Figure II.11: Freehand writing test.	36
Figure II.12: Live camera OCR test.	36
Figure II.13: Test the circuit setup and STM32 code.....	37
Figure II.14: Current shape of 1 second after steps lose.....	38
Figure II.15: Artificial intelligence application demo.....	39
Figure III.1: Types of stepper Motors.....	41
Figure III.2: A4988 pololu circuit driver.....	44
Figure III.3: One phase of a transistor bridge bipolar drive circuit [8]	45
Figure III.4: Full step and Microstepping Position	46
Figure III.5: Atmel Atmega328P Microcontroller chip.....	48
Figure III.6: Arduino Uno components	49
Figure III.7 : Arduino IDE Platform	50
Figure III.8 : Mechanical end-stop	51
Figure III.9: Optical end-stop.	52

Figure III.10 : Magnetic end-stop	53
Figure III.11 : Rotary encoder	54
Figure III.12 : Encoder schematics	55
Figure III.13 : CNC ATC Cartridge Spindle	56
Figure III.14 : Makita Trim Router: 1 1/4 HP high rpm spindle	58
Figure III.15 : Dramel 3000 spindle.	59
Figure III.16 : Schematics of controlling motor circuit	60
Figure III.17 : Filter and amplifier circuit.	61
Figure IV.1 : Infographic reference to quickly identify CNC materials	63
Figure VI.2 : Aluminium 6061 part.	65
Figure VI.3 : Stainless steel 304 part.	66
Figure VI.4 : Commonly used configurations of machine tools.	67
Figure VI.5 : V-type guideways.	70
Figure VI.6 : Flat guideways.	71
Figure VI.7 : Dove Tail Type Guideways.	72
Figure VI.8 : Cylindrical Type Guideways.	73
Figure VI.9 : Ball bearing schematics.	75
Figure VI.10 : Bushing bearing.	76
Figure VI.11 : Aluminium case bushing bearing.	76
Figure VI.12 : Stainless steel trapezoidal lead screw.	77
Figure VI.13 : Timing Belt Construction	78
Figure VI.14 : GT-2 Timing Belt.	78
Figure VI.15 : Our CNC machine design with SolidWorks.	79
Figure VI.16 : The volume of the maximum job work.	79
Figure VI.17 : The full size of the machine.	80
Figure VI.18 : Our CNC Machine Parts.	81
Figure VI.19 : Fixed geometry restraint inside of the bushing bearing.	86
Figure VI.20 : Applying external load at the router head.	86
Figure VI.21 : Creating the mesh model.	87
Figure VI.22 : The stress simulation at the at the stainless steel rods.	87
Figure VI.23 : The displacement simulation of the router head after the update.	88
Figure VI.24 : The displacement simulation of the router head.	88
Figure VI.25 : The displacement simulation of the table.	89
Figure VI.26 : The stress simulation of the table.	89
Figure VI.27 : The final building process.	91

List of tables

Table II.1: Different activation functions.....	25
Table VI.1: Summary table for metals.	64
Table VI.2: Coefficient of friction for leadscrew threads	82
Table VI.3: ISO threads specifications.....	83
Table VI.4: Building material properties	90

General introduction

The most commonly used modern technology for manufacturing products are CNC machines. CAD-CAM technology achieves new creative and innovative way with a wide range of applications. Thanks to that, we can experiment with different shapes and using unusual materials. The modern trend is using original natural materials with new advanced synthetic materials.

However, there are many obstacles that makes CNC machines not efficient or preforms tasks with errors. For one piece or two it's not that big of a deal, but imagine when we have a series of parts that's have to be machined and manufactured, and the machine got broken or the tools got destroyed. That's a time waste and time in the industry is money. Errors could be made by the machine itself, for example the CNC machine have many mechanical and electronical parts that's can lose their ability over time and makes the machine no longer operate like it's supposed to be. Human errors i.e. when an operator sends wrong commands to the CNC machine, it results an accident. Other errors are caused by the surrounding environment, i.e. an unstable floor installation causes vibrations and overheating that affects accuracy. The machine needs a steady outside environment to operate correctly.

We focused in our work, to improve the way the CNC machines operates, and try to reduce or to eliminate those main three errors.

The aim is to use Artificial intelligence to predict those errors, either by stopping the machine or by adjusting the appropriate speed. The solution requires a data collection step, a training step with supervised system and finally a testing step. Therefore we installed current sensors and encoders in all the stepper motors that moves the three axis and for the spindle of the machine. So we can store all the data information that we need and for all the possible scenarios. The current sensors will collect the input data and the encoders will collect the output data needed in the machine training process.

In our master's dissertation we design and build a CNC machine working with multilayer perceptron (MLP) library that we write in C# language. Our MLP library have been tested first with MNIST handwritten digit database. After that, we use our MLP library with the designed CNC machine to prevent errors and stop or to reduce speed when it is necessary.

Chapter I

Computer Numerical Control Machines

I.1 Introduction

In recent years, the goals of manufacturing systems have become more intense due to global competition in product development. In order to reach the market quickly, products need to be manufactured within time frames that are commonly used to produce prototypes. Consequently, this trend has attracted the attention of technology developers to improve the current manufacturing methods employed in making prototypes.

In terms of process capabilities, CNC machining employs a different mechanism in building the part which is totally opposite to AM processes. Cutting tools are used to penetrate and remove material from the work piece. Hence, a great variety of denser and stronger materials such as pure metals can be directly machined. In addition, greater part accuracy and superior surface finish are among the interesting features promised by CNC machining processes. Unfortunately, all these benefits do not in themselves fully justify the implementation of CNC machining for rapid processes.

In this chapter we are going to talk about the computer numerical control machines in different fields.

I.2 Definition

The face milling process is one of the most widely used and efficient means of machining materials at relatively high metal removal rates. Recently, in the interest of increased productivity, heavy cuts, which produce good finish machined surface, i.e. single-pass machining, have been emphasized. As a result, machine tools must be designed with rigid structures and spindles and in this regard, knowledge of the force system characteristics encountered in a given machining operation is invaluable for the analysis of deflection, chatter and vibration, and their effects on the quality of the finished product. Accordingly, a goal of studying face milling force characteristics is to develop a versatile computerized force model so that through computer simulation one can predict forces under commonly encountered conditions using databases easily established from straightforward machining tests so that material-based model parameters can be readily estimated [1].



Figure I.1: router CNC machine Badog class1.

I.3 History

Computer numerical control is a modern concept in the manufacturing and production industries. However, the concept of CNC harkens back to the basic idea of NC, or numerical control.

The idea of numerical control started when the automation of machine tools originally incorporated specific concepts of programmable logic. In the beginning, the first NC machines were built back in the 1940s. Slightly more advanced machines came along in the 1950s. These manufacturing machines were constructed based on existing tools that were modified with motors designed to move the controls of the machine. These controls followed specific points that were fed into the machine on punched tape. These early mechanisms were soon improved with both analog and digital computers. The introduction of computer technology into the concept of numerical control led to what we now know as computer numerical control.

I.3.1 Early MIT Research on Numerical Control

After World War II, John Parsons researched ways to improve aircraft by creating stiffened skins for them. This eventually led to a series of important Air Force research projects, which were conducted at the Massachusetts Institute of Technology (MIT). This research began in 1949. After the early planning and research phases, an experimental milling machine was

designed at MIT. Professor J.F. Reintjes and his team of researchers were involved in this project.

I.3.2 The First CNC Machine

Before the MIT projects, Parsons Corporation in Traverse City, Michigan developed a system to produce templates for helicopter blades. John Parsons, who founded the company, discovered how to calculate airfoil coordinates on an IBM 602A multiplier. He then fed these data points into a Swiss jig borer. To date, this was considered the first true numerical control machine as it manufactured goods – helicopter blade templates, in this case – by feeding punched cards into a system, and the system then read and produced the parts based on preprogrammed information.

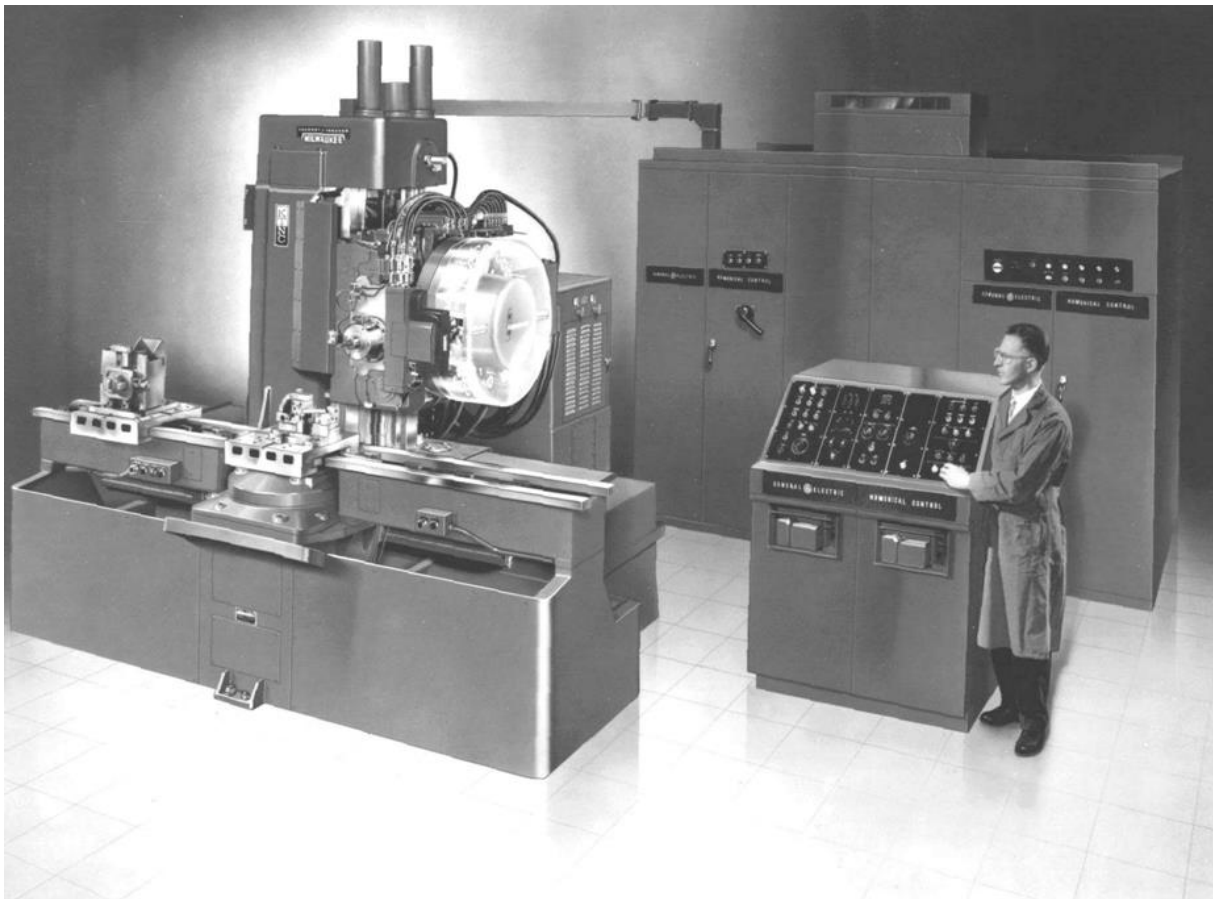


Figure I.2: first made CNC machine.

As numerical control technology moved into the 1960s and 1970s, a very familiar form of a CNC machine that most would recognize today started taking shape. Digital technology then entered the fray, and automation in production processes became more efficient than ever. In fact, many individuals can purchase – and even design – their own homemade CNC machines.

Because of how advanced computers are nowadays, it is more common than ever to find CNC machines in all industries.

I.4 Staples of CNC Technology

While there has been tremendous change in the history of CNC technology, a few cornerstones have remained unchanged. All automated motion control-manufacturing machines, from bare-bones concepts of the early days to highly advanced systems today, still require three primary components. These include a command function, a drive/motion system, and a feedback system. CNC has had a long and interesting history. As technology evolves in the future, there may be even more incredible elements to add to its history as manufacturing continues to promote the use of robotic and automated processes in nearly every field.

I.5 Area of use

These days the CNC machines are found in almost all industries, from a small scale industry to big companies. There is hardly any facet of manufacturing that is not touched by the automated CNC machining center. Everyone involved in the manufacturing should know what a CNC machine can do for their company. Due to extensive applications of CNC machines in various industries, there is a great surge in the demand of the CNC programmers. To meet these demands a number of schools have come up that teach the operation and programming of the CNC machines.

Here are some of the many industries where the CNC machining centers are used.

I.5.1 Industries for removing metal

The metal removing industries remove the metal from the raw material to give it the desired as per the requirements. These can be the automotive industries for making the shafts, gears, and many other parts. It can be manufacturing industries for making the various rounded, square, rectangular, threaded and other jobs. There are many other industries where the metal removal works are performed. All these metal removal works are performed by different machine tools like lathe, milling machine, drilling machine, boring machine, shaping machine, reamer, etc. Traditionally these machines are operated by the operators, but the CNC versions of all these machines are now used extensively. You can carry out almost all machining operations with

the CNC machining centers. You can also carry out all the turning operations such as facing, boring, turning, grooving, knurling, and threading on your CNC turning centers. On your CNC grinders you can carry out the grinding of the internal diameter, outer diameter, and also the flat surfaces. The Contour Grinding technology enables you to grind surfaces of all shapes.

I.5.2 Industries for Fabricating Metals

In many industries thin plates like steel plates are required for various purposes, in fabrications industry the machining operations are performed on such plates. In these industries the CNC machines are used for various machining operations like shearing, flame or plasma cutting, punching, laser cutting, forming, and welding and many other applications. To bring the plates to their final shape CNC lasers and CNC plasma cutters are used commonly. To punch the holes in the plates of all sizes CNC turret punch presses are used. And if you want to bend the plate so as to give it a final shape, you can use CNC press brakes. In some cases the CNC back gages are coupled with the shearing machines, this enables controlling the length of the plate to be sheared as for different applications.

I.5.3 Electrical Discharge Machining (EDM) Industry

The EDM machines remove the metal by creating the sparks that burn the metal. There are two types of EDM with the CNC automation – Vertical EDM and Wire EDM. The Vertical EDM needs an electrode of the shape and size of the cavity that is to be made in the job. Wire EDM is used to make the punch and die combinations for the dies set that are used in the industries where fabrication is done.

I.5.4 Other Industries where CNC machines are used

CNC machines are also used extensively in the wood working industries to perform various operations like routing (similar to milling) and drilling. CNC technology is also used in number of lettering and engraving systems. There are also CNC machines for the electrical industry such as CNC coil winders, and CNC terminal location and soldering machines.

In whichever the industry you go you are sure to find some or the other type of the CNC machine. The progress made by the manufacturing sector is mainly due to the advancements in the CNC technology.

I.6 Architecture types of CNC Machines

Some efforts to define an Open Architecture System will be addressed below:

I.6.1 OSACA Architecture (Open System Architecture for Controls within Automation Systems)

The OSACA (1998) architecture is a Control Open System Architecture for Automatic Systems. It appeared in Europe with the ESPRIT III Project 6379 program, being one of the largest projects involving standards for OAC (Open Architecture Control), that includes network connection and applications (Koren et al., 1996a).

The OSACA project began in 1992 in research institutes of France, Germany, Italy, Spain and Switzerland.

The main goal of the OSACA project was the definition of an independent hardware and modularity, that is, to work in modules allowing the addition or removal of numeric control, robot control, Programmable Logical Controllers (PLCs), cells control, etc. To manage these modules, it was created the OSACA phase II project 9115 to establish software modular systems, communication interfaces, operation and open data base systems for new functions and for the use in new digital equipment (Pritschow et al., 1993).

Following the same research line, it was created in Germany the HÜMNOS (Modulate Development for application in object oriented open architecture control system) project. This project development is based on the OSACA results. It had the participation of final users (BMW, Mercedes Benz), machine tool manufacturers (Alfing, Fritz Wener, Grunewald, Heller, Homag, Hüller Hille, Index, Mikromat, Pfauter, Trumpf and Unipo) and the controller manufacturers (Bosch, DASA, Grundig electronics, ISG, SIEMENS), along with of this project several research institutes.

The objective is to exchange information between users and manufacturers, bringing benefits to both. The OSACA architecture allows the assembly of the machine tool control using a user interface, without the need to review the whole software (Altintas, et al., 1996). To reach this goal it is necessary to know the concept of platform.

A platform is composed of hardware and program groups (operating system, communication system) that offer a uniform service for the functional unit (FU) control. The application-programming interface (API) with the FU is based on a well-defined task.

The three main platform areas are:

- Communication System: hardware and software are defined independently of the information exchange interface among different modules of the controller application. The OSACA

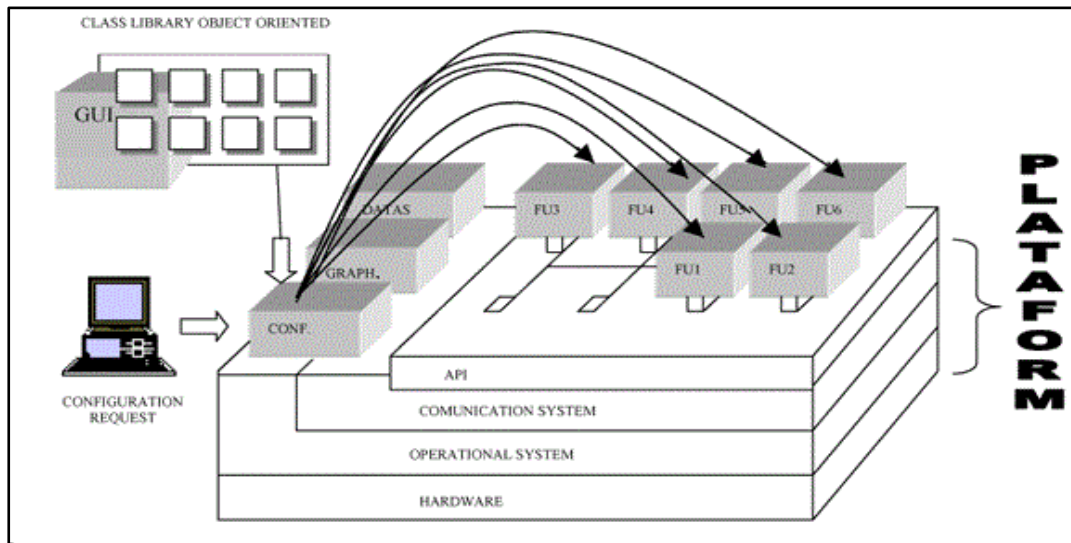


Figure I.3 System platform (OSACA, 1998)

communication system allows the information exchange in a transparent way between client and server applications.

- Reference Architecture: determines the control FU and specifies the external interface. This is done to enable the use and integration of external units through internal data in a well-defined way. FU examples are Man Machine Interface, Interlock Logical Control, and Axes Movement Control. For each identified FU, an external module using an object oriented communication for data interfacing with application modules is defined. The interface of writing and reading data access is located in the Architecture Oriented Object and this access is available with the use of a Communication Oriented Object.

- System Configuration: Allows a controller dynamic configuration through a combination of different application modules. This does not only allow determining a specific topology of a given functionality, but also the synchronization among the distributed processes.

Figure 1 describes the platform of the OSACA system, where a configuration request generated by a microcomputer is sent to the system. The reconfiguration uses FU, which works, based on object oriented programs, a class library, with variables and internal data. The OSACA application protocol uses a client/server base mounted on the object orientation principle. All FU functionality will have external access and it is configurable by the communication platform. From the customer's viewpoint, the server can be accessed through shipping and reception of system communication messages.

I.6.2 OMAC Architecture (Open Modulate Architecture Controllers)

The OMAC architecture had its beginning in December of 1994 with the publication of "Requirements of Open, Modulate Architecture Controllers for Applications in the Automotive Industry" by Chrysler, Ford and General Motors. This document served as a guide for controllers API in the North American automobile industries.

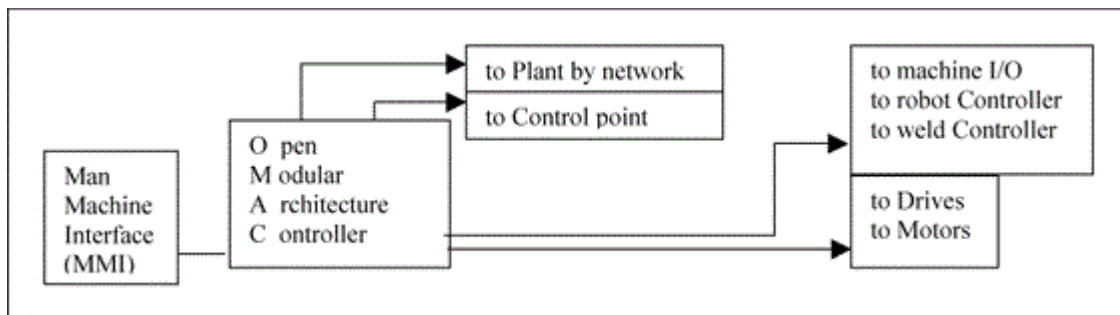


Figure I.4: OMAC System simplified plant (Yen, 1998)

The OMAC group is composed of open architecture system users, whose objective is to work together, bringing several benefits (Yen, 1998), such as:

- To establish a position of the open architecture controllers based on experience of the software users and machine manufacturers;
- To accelerate the open control use within the industries, with the use of APIs;
- To promote the development of open control among controller manufacturers;

- To develop collective solutions for the development, commercialization and use of open architecture controller technology.

I.6.3 HOAM-CNC Architecture (Hierarchical Open Architecture Multi-processor - CNC)

The HOAM-CNC architecture – Open System Architecture Hierarchical Multi-processor for CNC machines-acts mainly in the machine hardware, offering the advantages of having two buses, a CNC control bus and another bus to allow the introduction of new components. Some research centers involved in this research line are:

- University of Michigan/Ann Arbor, USA – which studies open architecture controller in real time for machines tools of high performance. They execute the implementation of several different types of hardware control with net communications to study the difference in machine performance depending on the adopted architecture (Koren et al., 1996^a; (Koren et al., 1996b).
- University British Columbia/Vancouver, Canada - they use this architecture seeking the regulating adaptive control. Modules that detect tool damage and vibration are inserted using acoustic sensors for the control execution. A primary bus is used to execute the machine control process and to monitor the tasks and a secondary bus of higher performance is used to communicate with the CNC (Altintas et. al., 1996) (Yamazaki, 1996).

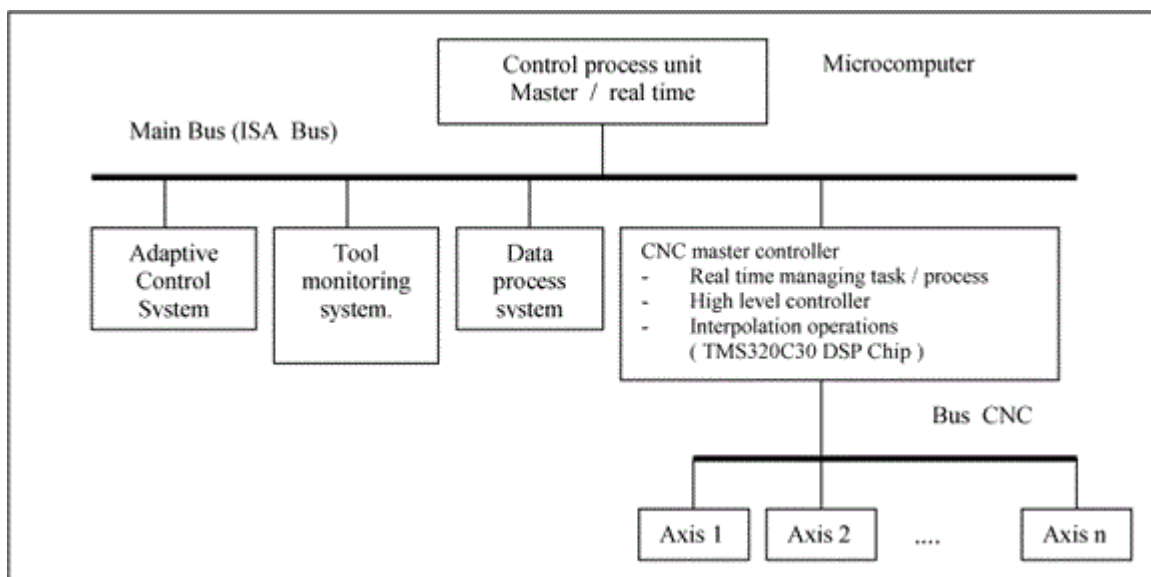


Figure I.5: HOAM-CNC Hardware global architecture.

Figure 3 illustrates the HOAM-CNC architecture where a microcomputer is used. The standard main bus ISA deals with the monitor activities, data processing, adaptive control and man machine interface (MMI). The CNC bus deals with the position and speed control of each axis (Altintas et al, 1996), operating the control in real time with a dedicated processor.

The system allows the addition of several processing modules in the primary bus and the interaction of control axes in the secondary bus.

I.6.4 OSEC Architecture (Open System Environment for Controller)

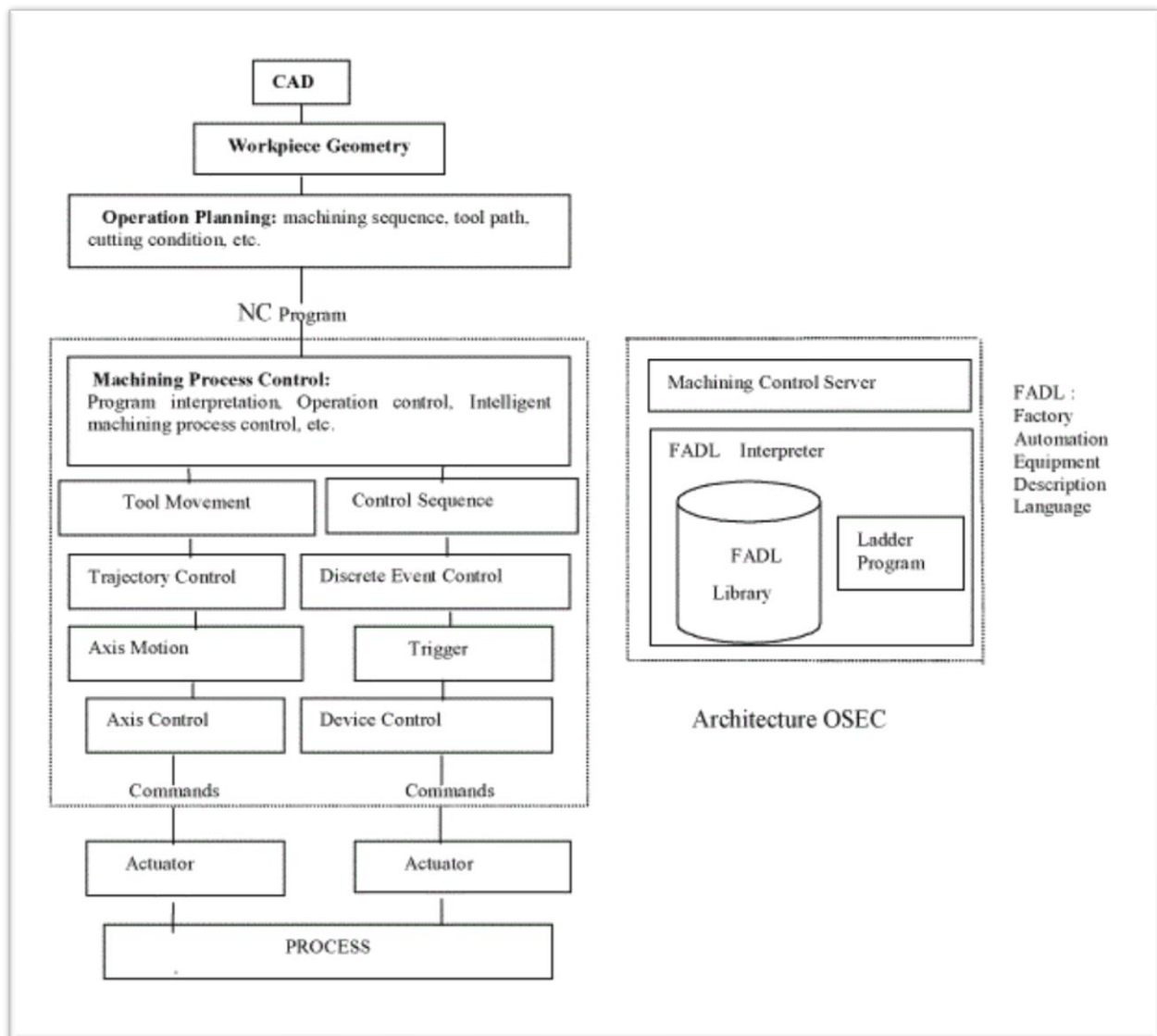


Figure I.6: Architecture OSEC.

Six Japan companies, Toshiba Machine Co., Toyoda Machine Works Ltd., Yamazaki Mazak Co., IBM Japan Ltd., Mitsubishi Electric Co., SML Corporation, composed the OSEC (Open

System Environment for Controllers) group, whose objective was to develop a platform of open architecture for numeric control equipment.

The purpose of this group is to create an open architecture based on a standard personal microcomputer IBM-PC to control manufacturing equipment, to improve its performance and to facilitate its maintenance. The personal microcomputer besides controlling equipment can also act as an information base system for the factory operation. In other words, pieces of equipment based on this architecture can be elements of an acquisition and logistics support system based on computer - CALS (Computer-aided Acquisition and Logistic Support) (Yamazaki, 1996).

There are many research centers working on this open architecture concept, such as the USA Navy with the enhanced machine controller project - EMC (Enhanced Machine Controller), with the Trade Department support that proposed a five level architecture:

- 1 - workstation planning;
- 2 - workstation managing;
- 3 - plan interpretation;
- 4 - trajectory generation/ discrete input and output (I/O).
- 5 - servo controls.

The project includes thermal deformation error compensation and NURBS (Non Uniform Rational B-Spline) interpolation (Yamazaki, 1996).

The USA Energy Department with the TEAM-ICLP (Technologies Enabling Agile Manufacturing - Intelligent Closed Loop Processing) project concentrates its researches on the development of an API oriented to open architecture.

The National Center for Manufacture Science (NCMS) that launched the NGIS (Next Generation Inspection System II) project is seeking the development of a sensor process inspection interface.

I.7 CNC milling machine components

I.7.1 the Frame

A CNC Milling Machine Frame supports the machine and provides rigidity to resist cutting forces. Typically, there is a base with a detachable column.

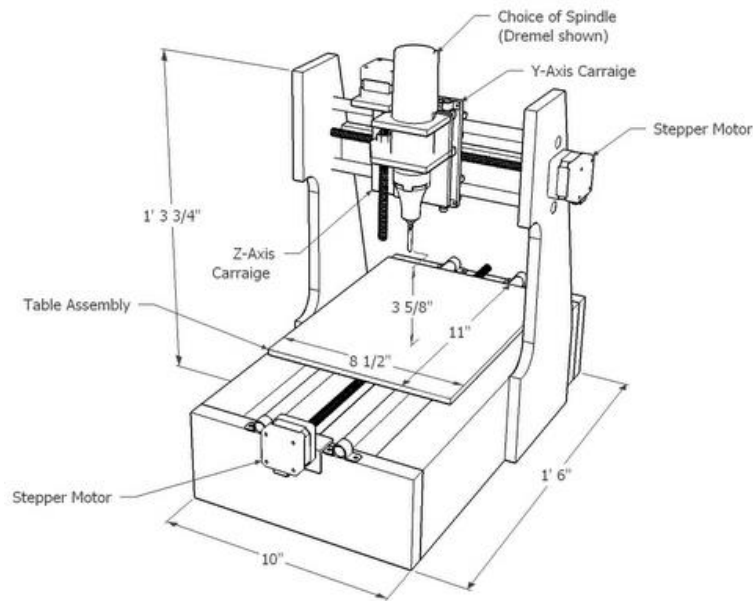


Figure I.7: Main frame of a DIY CNC machine.

I.7.2 Table

The table is where a work holding solution of some kind holds the work piece for machining. Most milling machine tables use T-Slots to attach work holding to the table. You can make a T-Slot table even more useful and versatile by mounting a Fixture Plate on it.

I.7.3 Spindle

The spindle is the heart of any milling machine. It consists of a rotating assembly with a taper where tool holders may be installed.

A motor with optional transmission of some kind rotates the spindle.

I.7.4 Axes

The axes of a CNC milling machine allow motion using cartesian coordinates programmed via g-code and via manual jogging from the control panel. Generally, there are 3 axes that correspond to X, Y, and Z. An optional 4th Axis is an accessory for CNC Milling Machines. 5 axis milling machines are possible but not very common in the DIY CNC world.

I.7.5 CNC Controller

The CNC Controller is the brains of the machine. It contains the electronics that drive the axis motors to move the axes.

CNC Controllers are responsible for accepting G-Code and manual inputs from the CNC Control Panel and converting that into the proper signals to control the Axis Stepper or Servo Motors.

I.7.6 Motors

When it comes to powering a CNC machine, the heart and soul of the machine relies in the motor. The CNC routers speed, accuracy, and precision all rely on the size and type of the motor. The two primary motor classes that are used with CNC machines are stepper motors and servo motors.

The name "stepper" comes from the steps made by the motor with every signal pulse. It is simple to operate, inexpensive compared to servo motors and has a high reported accuracy. Its low speed torque enables the use of a pulley reduction and timing belt, allowing several loads to be driven without gearing.

I.7.7 Power supply

The power supply in this case is to power the stepper motors, spindle and the main board in a computer-controlled milling machine. The device consists of start-stop system with signaling status, transformer's soft-start, unstabilized and stabilized power supply with 12V output voltage and ampacity 1A. The power supply is equipped with a number of security features and automatic layout of the capacitors discharges after switching off the power supply.

I.7.8 G-code and M-code

In modern CAD and CAM manufacturing companies, engineers design parts for machines and consumable goods. Many of these parts are cut on CNC machines. Whether using a CNC lathe, milling machine, or router, the ideas and designs of engineers must be translated into a machine-readable form called G & M Code that can be used to cut parts to precise dimensions and tolerances. Machine operators and engineers must be able to read the G & M Code that forms the basis of communicating with CNC machines. If there is a problem in manufacturing a part, the ability to read and write G & M Code is crucial to getting production back on line quickly.

G Code is a **Geometric Code**, which is used for make a geometry/profile of a component having cylinder/bar in CNC lathe or rectangular plates in CNC milling.

M code is a **Machine Code or Miscellaneous Code**, which is used for machine functions in all CNC machines. For example Coolant on/off, Spindle Speed on/off, tool change and machine stop permanent/temporary etc.

7.8.1 *Example of G-code and M-code commands*

- Non-Modal Commands: G4, G10L2, G10L20, G28, G30, G28.1, G30.1, G53, G92, G92.1
- Motion Modes: G0, G1, G2, G3, G38.2, G38.3, G38.4, G38.5, G80
- Feed Rate Modes: G93, G94
- Unit Modes: G20, G21
- Distance Modes: G90, G91
- Arc IJK Distance Modes: G91.1
- Plane Select Modes: G17, G18, G19
- Tool Length Offset Modes: G43.1, G49
- Cutter Compensation Modes: G40
- Coordinate System Modes: G54, G55, G56, G57, G58, G59
- Control Modes: G61
- Program Flow: M0, M1, M2, M30
- Coolant Control: M7, M8, M9
- Spindle Control: M3, M4, M5
- Valid Non-Command Words: F, I, J, K, L, N, P, R, S, T, X, Y, Z

7.8.2 *Some of the function commands*

- **G00:** The Rapid Movement G-code, known as G00 tells the machine to move as quickly as it can, with no synchronization of the axes. The machine will move relative to the absolute position set initially or through offsets. The G00 G-code can also be written as G0, and most CNC programs can accept either G00 or G0. We use G0 in our examples to save space, which is important when using software such as GRBL.

Standard Format:

```
G00 X0.000 Y0.000 Z0.000
```

- **G01:** The Linear Interpolation G-code, known as G01 allows the machine to move with exact synchronization of all its axis. The machine will move relative to the absolute position set initially or through offsets. The G01 G-code can also be written as G1, and most CNC programs can accept either G01 or G1. We use G1 in our examples to save space, which is important when using software such as GRBL.

Standard Format:

```
G01 X0.000 Y0.000 Z0.000 F100.0
```

- **M00:** This is known as the Program stop M-Command known as M00. This command is useful to be run whenever a stop is desired. The machine will pause in its place until the machine control software gives a start command. Sometimes also known as a 'Feed Hold'. Once a M00 command has been triggered, typically the only way to resume the program is for the operator to enter a Cycle Start command using the CNC Control Software. The program will resume on the following line.

Standard Format:

```
M00
```

- **M03:** For CNC machines equipped with a remote activated spindle, the M03 M-Command will activate the spindle in the clockwise direction. For CNC machines with a pulse width modulated (PWM) spindle, an additional parameter will set the speed, typically calculated in RPM.

For spindles with a slow spin up time, it is crucial to place a G04 dwell command after the spindle start to ensure it has enough time to get up to full speed.

Standard Format:

M03 S00000

I.8 Software

The software involves the building of an interpreter for the part program. The part program executed by the microprocessor consists of a series of instructions. Each instruction comprising a string of binary digits is decoded by the microprocessor and is then executed. The microprocessor requires these instructions to be written in Op-codes. An Opcode is an instruction that is composed of hexadecimal characters. The interpreter translates the G-codes into equivalent Op-codes. The software for the system is designed to generate automatic stops for the tool and work piece movements. This is done because the unit operates in the open loop mode.

The backlash in the screw rod is estimated and the software is corrected for this error. The system software is developed by adopting the modular programming format. A module may be termed as a subroutine that forms a part of the main program. Every module comprises a set of general purpose instructions that can be accessed when required during the course of execution of the program. All the G-codes require stepping motors to be switched on and off.

One module is set apart for switching on the stepper motors. This module is accessed by all the 'G' functions which mean that this module does not belong to any particular G-code. Initially, the system software is loaded in random access memory (RAM) of the microprocessor for testing purposes. After the credibility of the program has been established, the addresses of the Op-codes are located in the ROM (read only memory) area designated by the makers of the microprocessor kit.

The programs are then loaded into an erasable programmable read only memory (EPROM) to form a permanent part of the system, until a hardware erasure is affected. This is in contrast to the operation of a RAM, which loses its contents once the system is switched off. The EPROM instructions are not accessible to the user. By removing the EPROM from the system software for milling, and inserting another EPROM into the microprocessor, which perhaps has lathe

system software, the controller that is used to control a CNC 12 milling machine can then be used to control a CNC lathe.

Once the software has been developed and tested, the manufacture of the system proves easy because the general purpose microprocessor loaded with this software in ROM becomes specific to the machine tool. The machine operates in two modes - the manual mode and the automatic mode. The manual mode allows the motion in the machine to be controlled by manually pressing the appropriate keys. The automatic mode allows the execution of the instructions in the part program. First, the machining parameters are determined. Second, the optimal sequence of operations is evaluated. Third, the tool path is calculated. Fourth, a program is written. Each line of the program, referred to as a block, contains the required data for transfer from one point to the next.

I.8.1 GRBL software

GRBL is a no-compromise, high performance, low cost alternative to parallel-port-based motion control for CNC milling. It will run on a vanilla Arduino (Duemillanove/Uno) as long as it sports an Atmega 328.

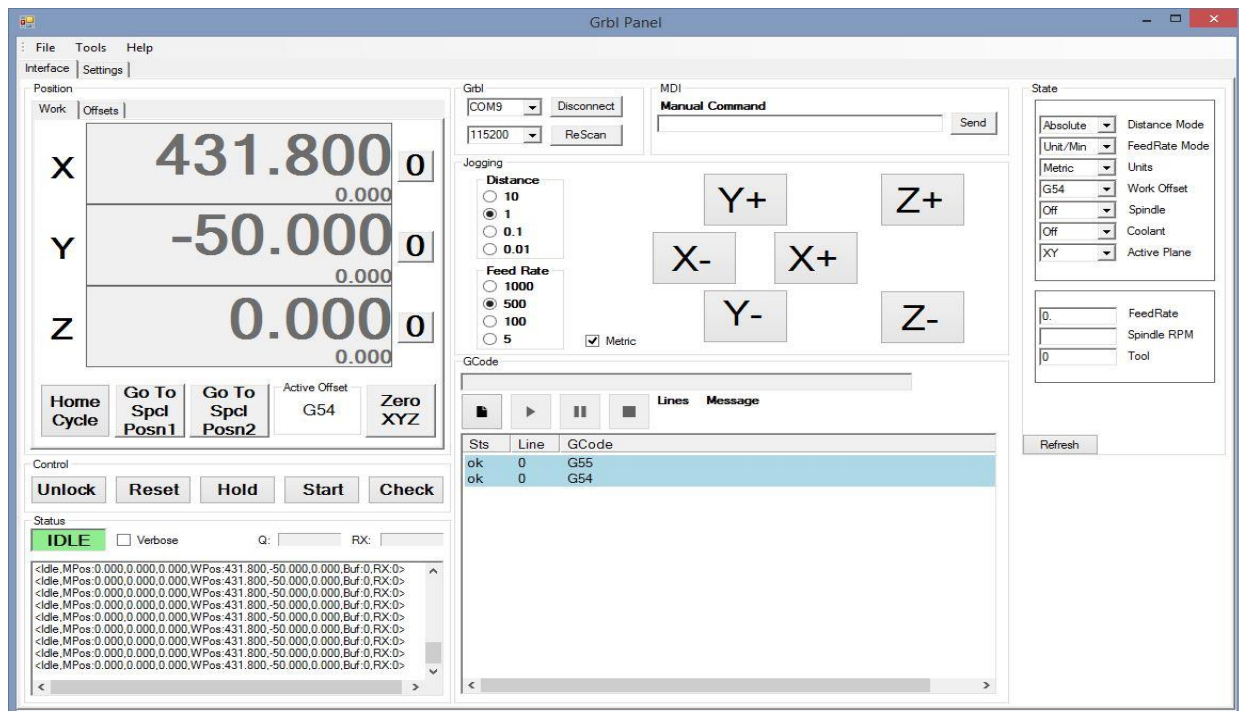


Figure I.8: GRBL Software desktop platform.

The controller is written in highly optimized C utilizing every clever feature of the AVR-chips to achieve precise timing and asynchronous operation. It is able to maintain up to 30kHz of stable, jitter free control pulses.

It accepts standards-compliant g-code and has been tested with the output of several CAM tools with no problems. Arcs, circles and helical motion are fully supported, as well as, all other primary g-code commands. Macro functions, variables, and most canned cycles are not supported, but we think GUIs can do a much better job at translating them into straight g-code anyhow.

Grbl includes full acceleration management with look ahead. That means the controller will look up to 18 motions into the future and plan its velocities ahead to deliver smooth acceleration and jerk-free cornering.

I.9 Conclusion

CNC machine is the most popular in the industry of creating parts. These machines offer extreme precision at a fast rate, CNC machines are very complex and able to efficiently operate one takes much time and practice. Although most of the operational codes are similar, CNC machines are different from model to model. CNC milling is not easy at first but mastery of it allows you to create a plethora of usable parts in a very short time frame.

Chapter II

Artificial Neural Network

II.1 Introduction

Artificial intelligence (AI) is the simulation of human intelligence processes by machines, especially computer systems. These processes include learning (the acquisition of information and rules for using the information), reasoning (using rules to reach approximate or definite conclusions) and self-correction. Particular applications of AI include expert systems, speech recognition and machine vision.

AI can be categorized as either weak or strong. Weak AI, also known as narrow AI, is an AI system that is designed and trained for a particular task. Virtual personal assistants, such as Apple's Siri, are a form of weak AI. Strong AI, also known as artificial general intelligence, is an AI system with generalized human cognitive abilities. When presented with an unfamiliar task, a strong AI system is able to find a solution without human intervention.

In this chapter, we are going to approach what Artificial intelligence is, and where it can be used and what's its properties, mostly we are going to talk about a type of AI called Neural Network.

II.2 Definition

A neural network (NN) is a small computer model of the human brain. The human brain contains about 10¹¹ units called neurons. These neurons are interconnected with approximately 10¹⁵ links. Although more research is needed, the neural network of the brain is considered as the fundamental functional source of intelligence, which includes perception, cognition, and learning for humans as well as for other living beings [5].

Similar to the brain, a neural network is composed of artificial neurons (or units) and interconnections. When we view such a network as a graph, neurons can be represented as nodes (or vertices), and interconnections as edges [5].

Although the term "neural networks" (NNs) is most commonly used, other names include artificial neural networks (ANNs) to distinguish from the natural brain neural networks neural nets, PDP (Parallel Distributed Processing) models (since computations can typically be performed in both parallel and distributed processing), connectionist models, and adaptive

systems [5]. We will provide additional information on neural networks in a later section of this chapter.

II.3 Biological neural network

A biological neural network is an essential part of human brain. It is a highly complex system with the ability to process large amounts of information simultaneously. Biological networks are able to recognize and process different visual inputs much faster than any modern high-end computer. For example, human brain is able to recognize familiar face in about 100-200 ms, while modern computer requires minutes or even hours for solving the same problem. In general, it is a known fact that in many tasks, human brain is much more efficient than computers. Based on examples and feedback from the "teacher", our brain allows us learning how to distinguish an apple from an orange or recognize letters. Even without the "teacher", we are still able to group similar patterns together. Those and other strengths of human brain, challenged scientists to emulate those processes by researching how to use machines for tasks that are common for humans. One of the concepts that appeared as the result of that research, is the Artificial neural network (ANN) concept. First steps of the ANN theory were made in 1943 by neuro-physiologist Warren McCulloch and mathematician Walter Pitts. They introduced artificial neurons with the threshold that could be arranged into networks.

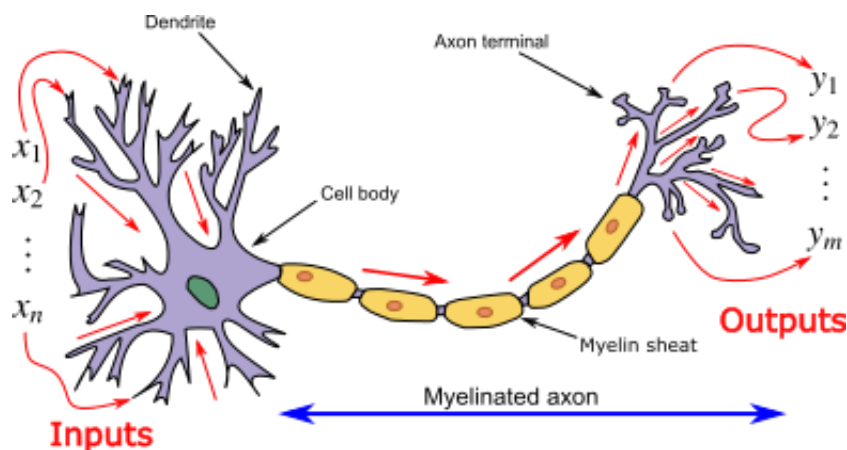


Figure II.1 Model of the biological neuron.

Several years later, in 1949, a psychologist Donald Hebb designed the first learning rule for artificial neural networks - Hebb's rule. Its premise was that if two neurons were active simultaneously, then the strength of the connection between them should be increased. In

Chapter II Artificial Neural Network

subsequent years, the ANN theory made significant progress: in 1960s more neuron architectures as perceptron and adaline were introduced. Next years, jointly with more powerful computers, brought even more different types of ANN-self-organizing maps, associative networks, RBF-networks and more. Nowadays, artificial neural networks are widely adopted by different scientific and industrial fields from medicine to speech recognition. More about ANN history can be found in [2].

Scientists started their attempts in discovering human brain secrets long time ago. But despite the fact that in previous centuries the neuroscience made a huge breakthrough, there are still numerous mysteries about how human brain works [3][4]. One of the very first scientific attempts of discovering the main principle of brain functioning was made by Santiago Ramon y Cajal in 1911. He used the method of Camillo Golgi for silver nitrate preparation, and then dyed brain neurons using that substance. Cajal discovered that brain has a cell structure and described brain cells as a polar-sensitive cells that receive signals using ramified sprouts (called dendrites) and send signals using formation called axon. Axon contacts dendrites of other neurons through special connection points synapses that adjust strength of the input signal (Fig. II .1).

Golgi method helped to discover a great variety of neurons which differ in dendrites branching and axons length. Cajal found numerous differences between the types of neurons. However, despite all those distinctions, they all process signals in the same way: signals are represented by electric impulses that are transmitted across a synaptic gap and dendrites to the soma. Soma, neuron's body, then somehow sums up the incoming signal. If the result is greater than some threshold value, the cell fires and transmits a signal over its axon to other cells. Also, the synaptic behaviour can change in time, so the neuron's behaviour changes as well. Cajal concluded that synapses play an important role in learning. The whole learning process is based on synaptic weights adjustments.

II.4 How artificial neural networks work?

A neural network usually involves a large number of processors operating in parallel and arranged in layers. The first layer receives the raw input information -- analogous to optic nerves in human visual processing. Each successive tier receives the output from the layer preceding it, rather than from the raw input -- in the same way neurons further from the optic nerve receive signals from those closer to it. The last tier produces the output of the system.

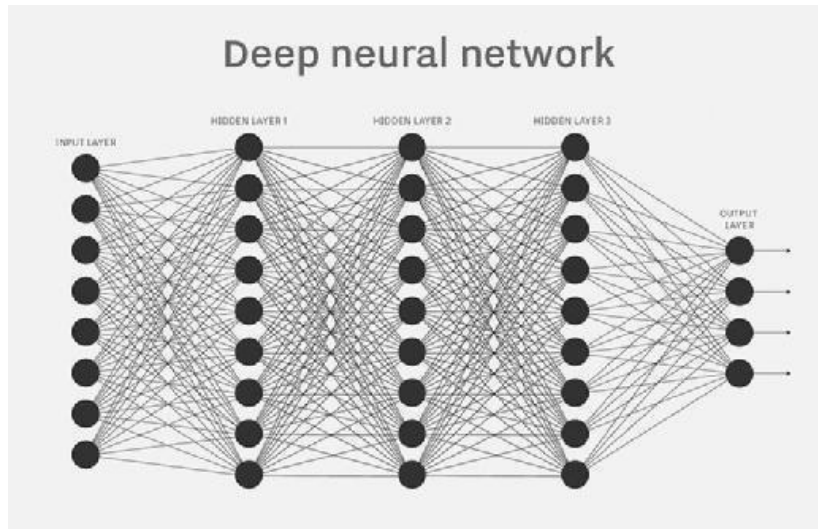


Figure II.2 Neural network multiple layers

Each processing node has its own small sphere of knowledge, including what it has seen and any rules that has been originally program + med with or developed for itself. The layers are highly interconnected, which means each node in layer n will be connected to many nodes in layer $n-1$ -- its inputs -- and in layer $n+1$, which provides input for those nodes. There may be one or multiple nodes in the output layer, from which the answer it produces can be read.

Neural networks are notable for being adaptive, which means they modify themselves as they learn from initial training and subsequent runs provide more information about the world. The most basic learning model is centered on weighting the input streams, which is how each node weights the importance of input from each of its predecessors. Inputs that contribute to getting right answers are weighted higher.

II.5 Mathematical model of the neuron

Biological neural networks are very complex. In contrast, the mathematical model of the network is much more simplified and is based on several assumptions:

1. All neurons are synchronized. That means that the signal passing from one neuron to another takes the same time for all connections. Signal processing is also synchronized and is the same for all neurons.
2. Every neuron has a so-called transfer function, which determines neuron's output signal depending on the input signal strength. That function is time-independent.
3. When the signal passes the synapse, it changes linearly, i.e., some number multiplies the signal value. That number is called synaptic weight.

The very important property of the synaptic weight is that it changes in time. That feature makes it possible for brain to react differently on the same input in different moments, or in other words, to learn. Of course, these assumptions simplify the initial biological neural network very much. For example, brain signal transmission time, naturally depends on the distance between neurons. Nevertheless, despite simplifications, artificial networks still preserve the most important characteristics of biological networks: adaptability and ability to learn. The first mathematical model of the neuron was introduced more than a half century ago, but it did not change much since then. First of all, the neuron is seen as a simple "automate" that transforms input signals into the output signal.

The model functions as follows: inputs of the neuron's synapses receive N signals $[x_1, \dots, x_n]$. Then every synapse makes a linear modification of the signal using its synaptic weight. After that neuron's body (soma) receives signals $[x_1 w_1, \dots, x_n w_n]$ (where w_i is the corresponding synaptic weight) and sums those signals:

$$S = \sum_{i=1}^m X_i w_i \quad (\text{II. 1}) [16]$$

Then it applies some given function F (that is also called activation function) and sends the final signal to the output.

$$Y = F(S)$$

(II. 2) [16]

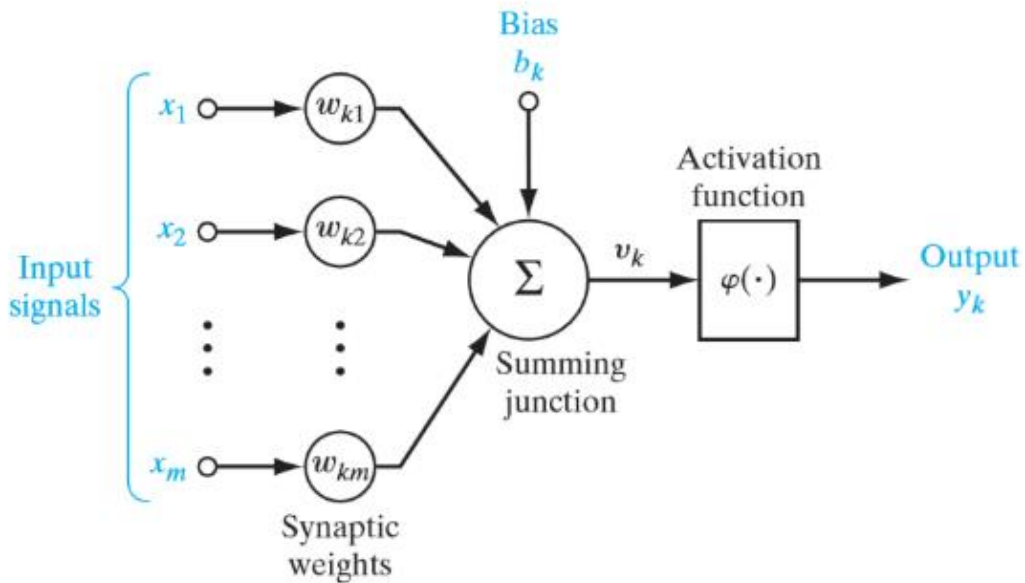


Figure II.3: Nonlinear model of a neuron, labeled k [16].

There are different activation functions. In a network, it is not necessary to use the same function for all the neurons, but it is a common practice. In most cases, activation functions are non-linear. Otherwise, the whole network will implement some linear transformation and will be equivalent to only one artificial neuron perceptron. Most common activation functions are listed below:

Where $\alpha \in \mathbb{R}$.

Function name	Formula	Values range
Linear	$F(S) = kS, k \in \mathbb{R}_+$	$(-\infty, \infty)$
Semi linear	$F(S) = \begin{cases} kS, S > 0, k \in \mathbb{R}_+ \\ 0, S \leq 0 \end{cases}$	$[0, \infty)$
Sigmoid	$F(S) = \frac{1}{1+e^{-\alpha S}}$	$(0, 1)$
Bipolar sigmoid	$F(S) = \frac{2}{1+e^{-\alpha S}} - 1$	$(-1, 1)$
Hyperbolic tangent	$F(S) = \frac{e^{\alpha S} - e^{-\alpha S}}{e^{\alpha S} + e^{-\alpha S}}$	$(-1, 1)$
Exponential	$F(S) = e^{-\alpha S}$	$(0, \infty)$
Sinusoidal	$F(S) = \sin(S)$	$[-1, 1]$
Fractional	$F(S) = \frac{S}{\alpha + S }$	$[-1, 1]$
Step	$F(S) = \begin{cases} 1, S \geq 0 \\ 0, S < 0 \end{cases}$	$[0, 1]$
Signature	$F(S) = \begin{cases} 1, S \geq 0 \\ -1, S < 0 \end{cases}$	$[-1, 1]$
Binary step	$F(S) = \begin{cases} -1, S \leq -1 \\ S, -1 < S < 1 \\ 1, S \geq 1 \end{cases}$	$[-1, 1]$

Table II.1: different activation functions.

II.6 Models of a neuron

A neuron is an information-processing unit that is fundamental to the operation of a neural network. The block diagram of (Figure II.3) shows the model of a neuron, which forms the basis for designing a large family of neural networks studied in later chapters.

Here, we identify three basic elements of the neural model:

- A set of synapses, or connecting links, each of which is characterized by a weight. Specifically, a signal x_i at the input of synapse i connected to neuron k is multiplied by the synaptic weight w_{ki} . It is important to make a note of the manner in which the subscripts of the synaptic weight w_{ki} are written. The first subscript in w_{ki} refers to the neuron in question, and the second subscript refers to the input end of the synapse to which the weight refers. Unlike the weight of a synapse in the brain, the synaptic weight of an artificial neuron may lie in a range that includes negative as well as positive values.
- An adder for summing the input signals, weighted by the respective synaptic strengths of the neuron; the operations described here constitute a linear combiner.
- An activation function for limiting the amplitude of the output of a neuron. The activation function is also referred as a squashing function, in that it squashes (limits) the permissible amplitude range of the output signal to some finite value.

Typically, the normalized amplitude range of the output of a neuron is written as the closed unit interval $[0, 1]$, or, alternatively $[-1, 1]$. The neural model of (Fig.II.3) also includes an externally applied bias, denoted by b_k . The bias b_k has the effect of increasing or lowering the net input of the activation function, depending on whether it is positive or negative, respectively. In mathematical terms, we may describe the neuron k depicted in (Fig.II.3) by writing the pair of equations:

$$u_k = \sum_{i=1}^m w_{ki} x_i \quad (\text{II. 3}) [16]$$

And

$$y_k = \varphi(u_k + b_k) \quad (\text{II. 4}) [16]$$

where x_1, x_2, \dots, x_m are the input signals; $w_{k1}, w_{k2}, \dots, w_{km}$ are the respective synaptic weights of neuron k ; u_k not shown in (Fig.II.3) is the linear combiner output due to the input signals; b_k is the bias; $\varphi(\cdot)$ is the activation function; and y_k is the output signal of the neuron. The use of bias b_k has the effect of applying an affine transformation to the output u_k of the linear combiner in the model of (Fig.II.3), as shown by

$$v_k = u_k + b_k \quad (\text{II. 5}) [16]$$

In particular, depending on whether the bias b_k is positive or negative, the relationship between the induced local field, or activation potential, v_k of neuron k and the linear combiner output u_k

Chapter II Artificial Neural Network

is modified in the manner illustrated in (Fig.II.4); hereafter, these two terms are used interchangeably. Because of this affine transformation, the graph of v_k versus u_k , no longer passes through the origin.

The bias b_k is an external parameter of neuron k . We may account for its presence as in Eq.(II.2). Equivalently, we may formulate the combination of Equations. (1) to (3) as follows:

$$v_k = \sum_{i=0}^m w_{ki}x_i \quad (\text{II. 6}) [16]$$

And

$$y_k = \varphi(v_k) \quad (\text{II. 7}) [16]$$

In Eq.(4), we have added a new synapse, its input is given as

$$x_0 = +1 \quad (\text{II. 8}) [16]$$

and its weight is

$$w_{k0} = b_k \quad (\text{II. 9}) [16]$$

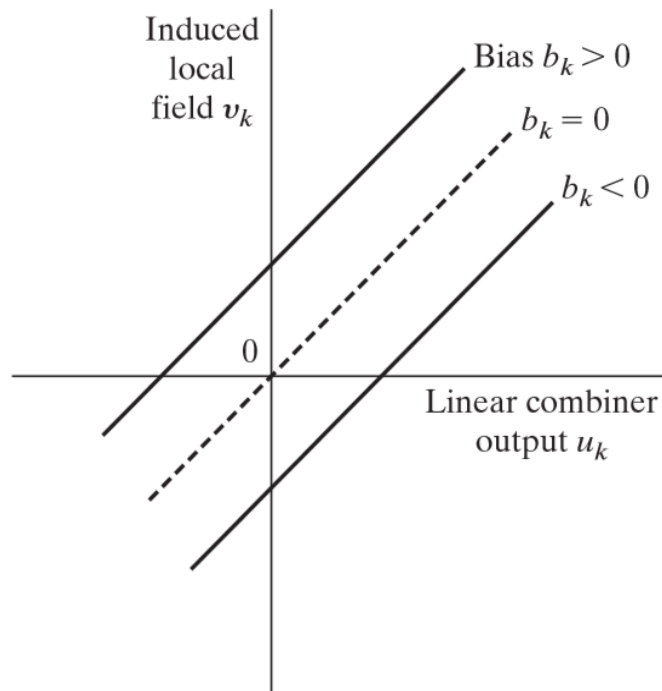


Figure II.4 Affine transformation produced by the presence of a bias; note that $v_k = b_k$ at $u_k = 0$ [16].

We may therefore reformulate the model of neuron k . In this figure, the effect of the bias is accounted for by doing two things: (1) adding a new input signal fixed at $+1$, and (2) adding a new synaptic weight equal to the bias b_k . Although the models of (Fig. II.3) and (Fig. II.5) are different in appearance, they are mathematically equivalent.

II.7 Multi-layer perceptron

That section describes one of the fundamental neural networks' types - multi-layer perceptron

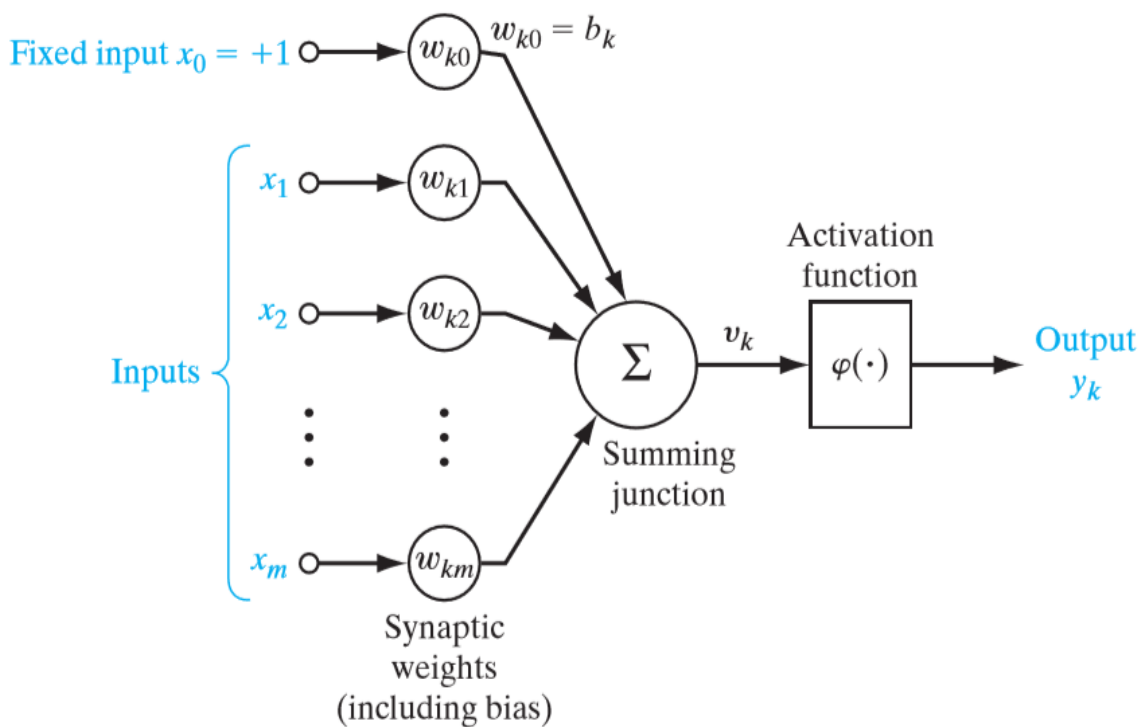


Figure II.5 Another nonlinear model of a neuron; accounts for the bias b_k [16].

(or MLP, or back propagation network). Many of other neural networks' types - such as RBF networks or probabilistic networks are based on that model. In general, an artificial neural network is a set of artificial neurons. Arrangement and types of those neurons depend on the network type. Multi-layer perceptron contains three types of neurons:

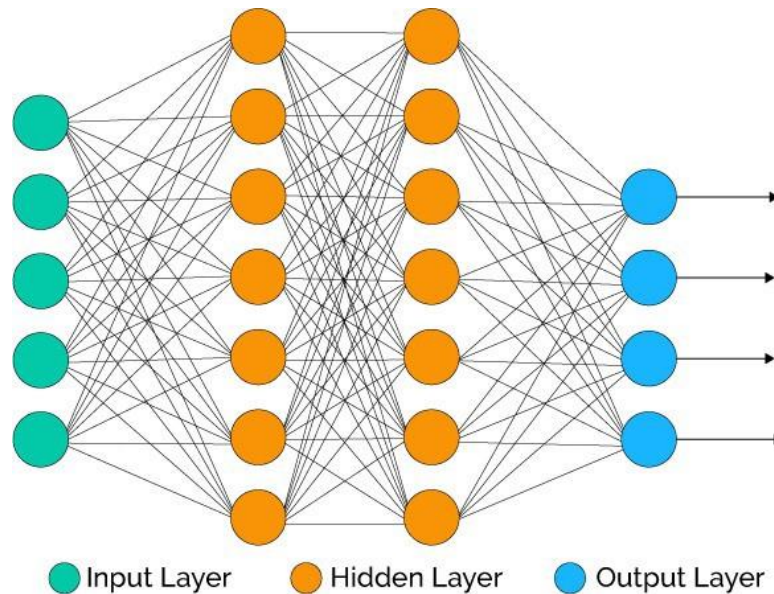


Figure II.6: Multi-layer perceptron.

II.7.1 Input neurons

Input neurons are taking input vector that encodes some action or information about the external environment. Input neurons do not perform any type of computation, but only pass the input vector to subsequent neurons.

II.7.2 Output neurons

Output neurons receive signals from the preceding neurons and transform it using formulas (II.1) and (II.2). Their values represent output of the completely neural network.

II.7.3 Hidden neurons

Hidden neurons are the basis of the neural network. These neurons receive the signal from the input neurons or preceding hidden neurons, process it in accordance with formulas (II.1) and (II.2) and then pass result signals to the subsequent (hidden or output) neurons.

In multi-layer perceptron, neurons are divided into multiple layers. Input and output neurons form separate layer each - input layer and output layer. Hidden neurons form one or several hidden layers. Every MLP neuron, with the exception of input neurons, is connected via synapses with all neurons of the previous layer. Example of the MLP architecture is shown on

Fig. II.6. The network receives 4-dimensional input (as it has 4 input neurons). The 4-dimensional output vector represents the result. It also contains three hidden layers. In publications, such network is often referred as 4-5-2-5-4.

II.8 Back propagation network training algorithm

Neural networks are the powerful tool for solving different problems - such as classification or prediction. However, in order to solve some particular problem, the network should be properly set up and then trained.

The very first step is the network architecture selection - e.g., how many input and output neurons should the network contain, how many hidden neurons and layers. Number of input and output units often follows the context. If the network is expected to produce boolean values, like "Yes" or "No", it is clear that it should have only one output. Similar thoughts can be applied to the input neurons' number. In contrast, selecting the number of hidden units and layers is not simple. In most situations, there is no obvious way of how to determine the best number of hidden neurons without training several networks and estimating the generalization error for each of them⁴. Too few hidden units will produce high training error due to underfitting. Too many hidden units lead to low training error but still have high generalization error due to overfitting. Some discussions about number of hidden units and layers can be found, for example, in [5] or [6].

The second step is training itself. **Back propagation algorithm** belongs to the group called supervised learning. It means that to be trained, the network should learn on pairs (input and expected output). In contrast, some classes of networks, like Kohonen's self-organizing maps, belong to the unsupervised learning group. It means that the training set does not contain expected outputs for the given inputs. Unsupervised learning is often used for clustering purposes. At the beginning of the MLP's learning, network's weights are initialized randomly (often by small random values). Then the network:

- 1) Processes one by one every item in the training set,
- 2) Compares its output with the desired output,
- 3) Computes error value and after checking the whole training set, the network modifies its synaptic weights in order to minimize the error.

Most of the MLP training methods are based on the gradient descent approach, i.e. iterative change of the network's synaptic weights that gradually decreases the error on the training

set. Algorithm that implements that idea is called error back propagation algorithm and can be described as follows:

1 Initialization

The first step is selecting the network architecture and setting its initial synaptic weights. The most common method of the synaptic weights initialization is choosing small random numbers with the zero mean value and uniform distribution.

2 Training pairs presentation

During that phase, elements of the training set are passed one by one to the network. For every training sample, there are two steps forward computation and backward computation - that are taking place.

3 Forward computation

Assume that the training set consists of N of pairs (x_i, d_i) :

$$T = \{(x_i, d_i)\}, i = 1, \dots, N, x_i \in \mathbb{R}^n, d_i \in \mathbb{R}^n \quad (\text{II. 10}) [16]$$

where x_i is an input vector and d_i is the desired output vector. The network passes the input vector from layer to layer and sequentially computes the outputs for all the layer's neurons. Those outputs form an input vector for the next layer. For every neuron j in the layer l (with the exception of input neurons) the output y_j^l signals are computed from the previous layer output signals y_i^{l-1} as follows:

$$S_j = \sum_{i=0}^{m_l} w_{ij}^l y_i^{l-1} \quad (\text{II. 11}) [16]$$

$$y_j^l = F(S_j) \quad (\text{II. 12}) [16]$$

Here m_l is the number of synaptic weights for all the neurons of the layer l . That number is determined by the number of neurons of the previous layer and is the same for every layer's neuron.

At first, the neuron calculates the linear combination of outputs of the neurons of the previous layer (II.11). The output value is calculated by applying neuron's activation

function to the value computed in the first step (II.12). For input layer - layer 0 - the formula is simpler:

$$y_j^0 = x_{ij} \quad (\text{II. 13}) [16]$$

where x_{ij} is the j^{th} element of the input vector x_i . After the input vector x_i passes all the layers, the network produces the output vector $o_i = [y_1^{\text{out}}, \dots, y_m^{\text{out}}]$, that is used for the error signal computation:

$$e_i = d_i - o_i \quad (\text{II. 14}) [16]$$

4 Backward computation

During that step synaptic weights are adjusted in order to produce smaller error value. Those adjustments are derived from the error signal. For each output unit j calculate δ_j^{out} :

$$\delta_j^{\text{out}} = e_{ij} F'(S_j) \quad (\text{II. 15}) [16]$$

Where e_{ij} is the j^{th} element of the error vector e_i and F' is the derivative function for the function F . For hidden neuron j of the layer l calculate δ_j^{hid} :

$$\delta_j^{\text{hid}} = F'(S_j) \sum_k \delta_k^{l+1} w_{jk} \quad (\text{II. 16}) [16]$$

Where summarization is done over all neurons k of the following layer, and w_{jk} is the synaptic weight that connects neurons j and k . When all δ are calculated, synaptic weights are adjusted using (II.17) and (II.18):

$$w_{jk}^{t+1} = w_{jk}^t + \Delta w_{jk}^t \quad (\text{II. 17}) [16]$$

$$\Delta w_{jk}^t = \eta \delta_j y_j^{l-1} + \mu (w_{jk}^t + w_{jk}^{t-1}) \quad (\text{II. 18}) [16]$$

where η is called learning rate, y_j^{l-1} is the output of the neuron j of the previous layer and μ is momentum. Learning rate and momentum are numbers between 0 and 1. They will be discussed later.

II.9 Application part

To apply the Neural Networks in our project we used C# language, which is an object-oriented programming language from Microsoft.

First, we implemented our neural networks library from scratch, it builds to support dynamic MLP (Multi Layers Perceptron) that means we can create any kind of module.

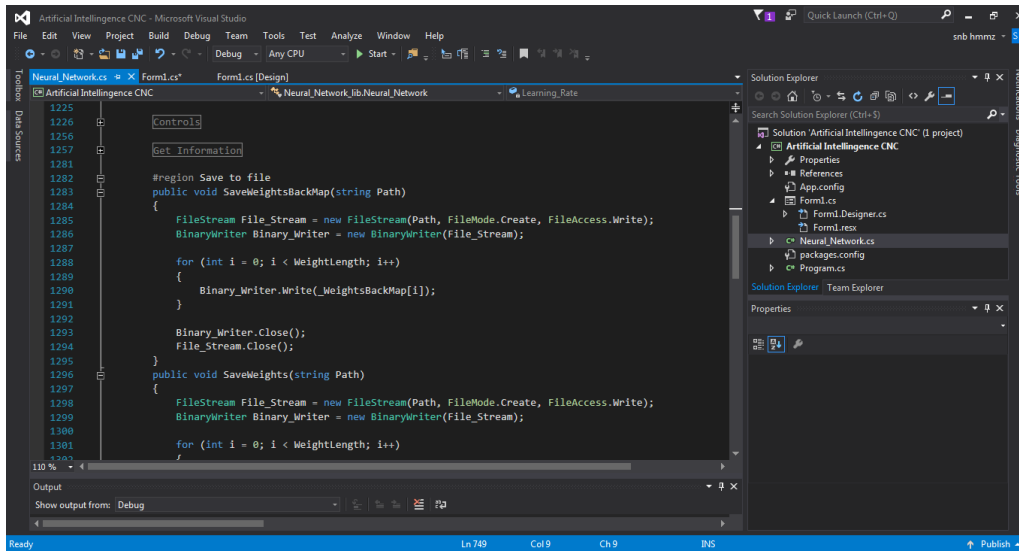


Figure II.7: Neural Network Library.

Our library can:

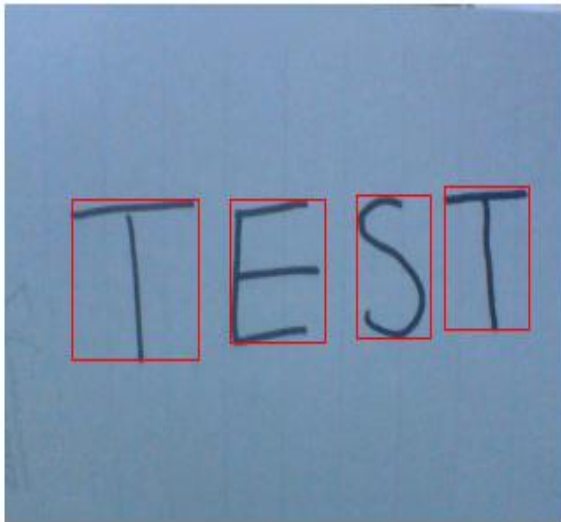
- Define the number of hidden layers.
- Define the number of neurons in input layer, hidden layers and output layer.
- Use different activation functions such as Sigmoid, ReLU, Leaky ReLU, TanH, Binary Step and Softmax.
- Use different Cost Function such Mean Square Error, Mean Absolute Error and Cross Entropy.
- Define learning rate.

II.9.1 Application of Real-time OCR Neural Network.

To prove that our library works fine and without bugs, we decided to create really time Neural Networks OCR (optical character recognition), which is the process of reading and converting typed, printed or handwritten characters into machine-encoded text or something that the computer can manipulate. Our Neural network OCR, achieves the following steps:

1. Read live video from the camera with size of 320 x 240 pixels at speed of 20 FPS (frame per second) then create two kinds of modes (normal mode / invert grayscale mode).
2. Filter this invert grayscale input images to reduce noises and prepare it for the next processing step.
3. Detect isolated objects (gets location and size).
4. Resize the detected objects to uniform size.

Default Camera



Processed Camera

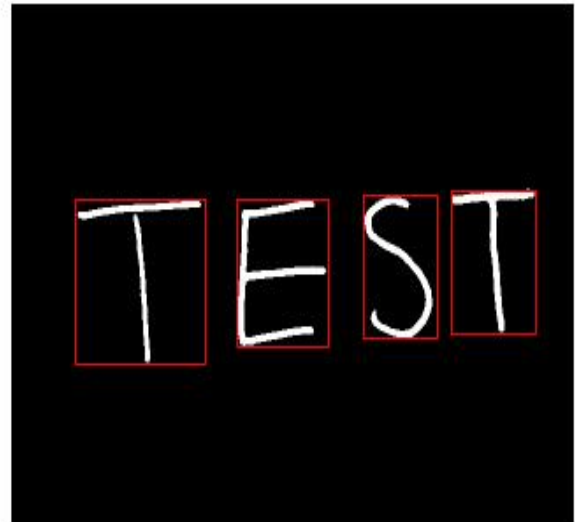


Figure II.8: Detecting objects.

To create our Neural Network module, we use 504 neurons in input layer to define the size of input images to 18 x 28 pixels and two hidden layers. First one contains 200 neurons and second one contains 80 neurons. The output layer has 26 neurons and represents the alphabets number.

- For Neural Network training, we use the MNIST dataset which contains 127400 images of upper-case character of training and 9000 images for testing.
- We use ReLU as activation function in both input layer and hidden layers and Softmax in output layer to classify the result, with learning rate of 0.001.

Chapter II Artificial Neural Network

In our application's training, we can visualise the training progress, the chart below shows the cost function evolution over the time. After waiting 272s (4min and 32s) we reach one epoch.

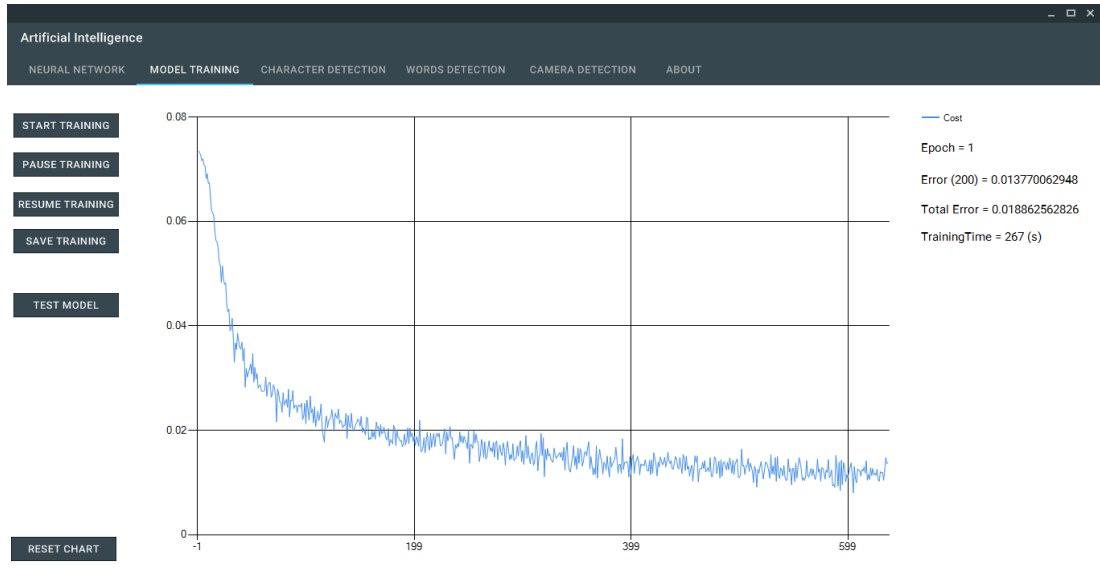


Figure II.9: Progress of the training.

For testing the model, we introduce the testing data one by one and search for the highest value of the output to compare it with the desire class, if it is above 80% we can say that the recognition is successful.

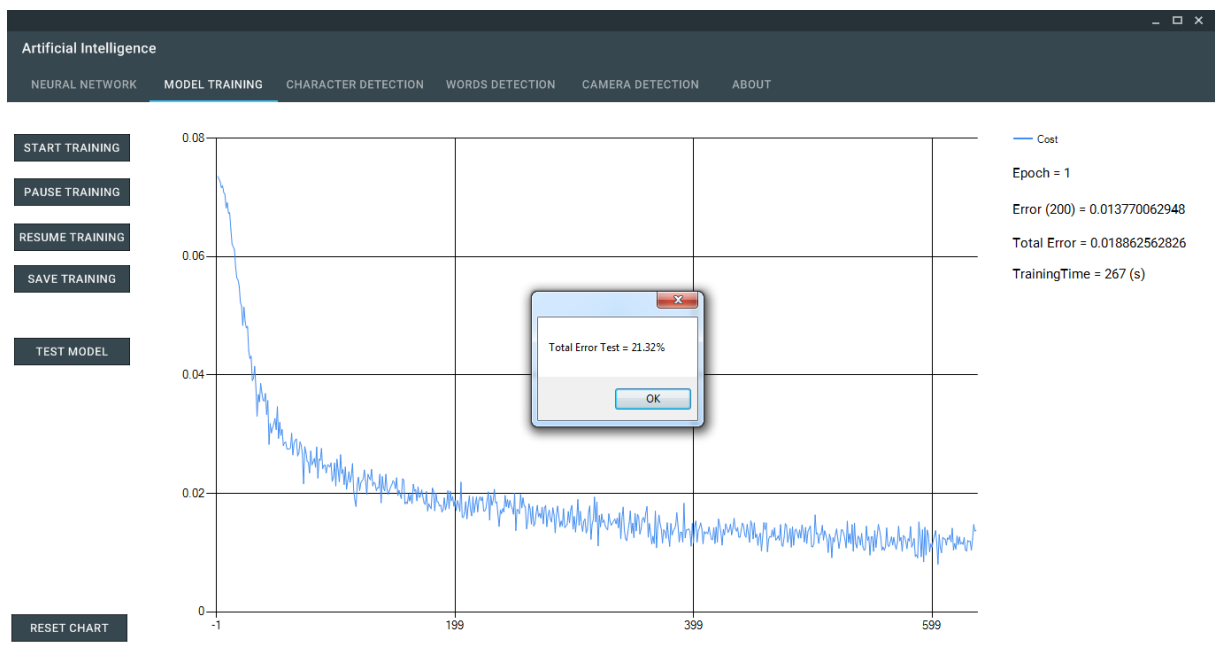


Figure II.10: Model testing

Chapter II Artificial Neural Network

The process is repeated until we introduce all the data, then we compute the number of times the model failed. After 10 epochs of training, we reach 6.20% of error, and we can test the model with our won data and see how it behaves.

For this example, we applied freehand writing. On the left side we have the input drawing panel with the output result. In the right side, we can see the input image given to the model and the model's output value.

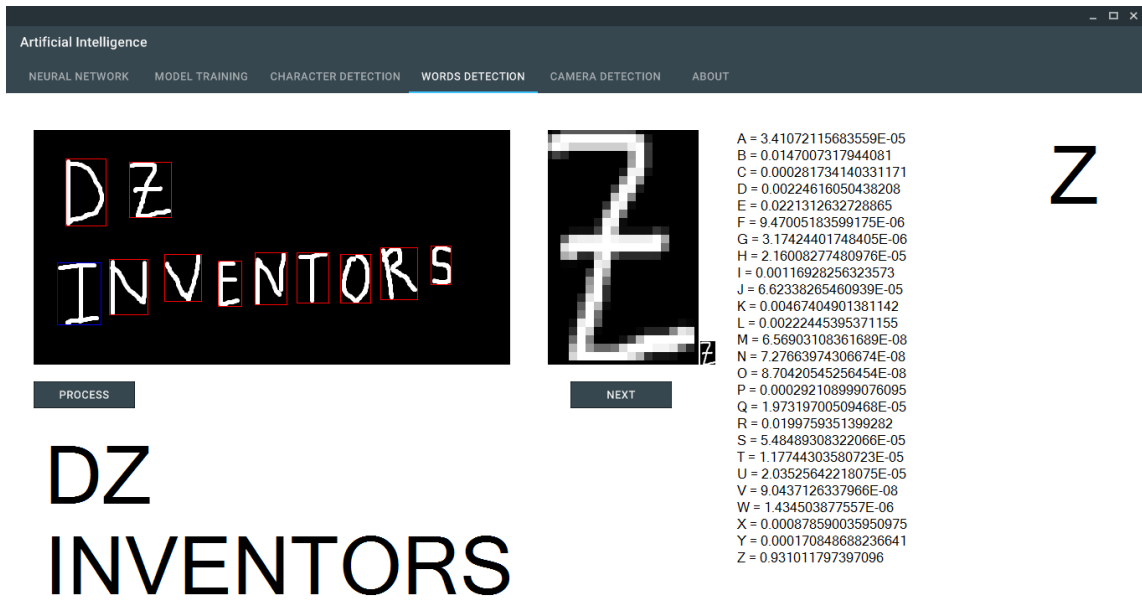


Figure II.11: Freehand writing test.

For the live camera OCR testing, we got this result.

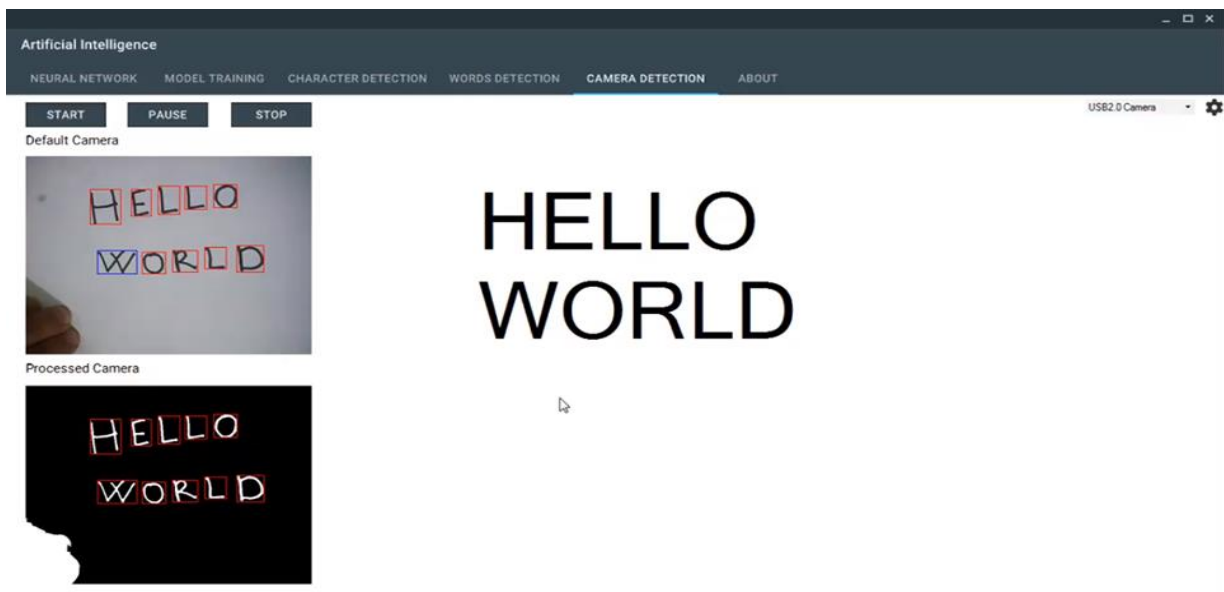


Figure II.12: Live camera OCR test.

II.9.2 Application of Neural Network in CNC Machine

After we prove the good functionality of our Neural Network library, we can now apply it to our CNC machine starting with X-axes, but first we need to collect the training data, to do so we do the following steps:

- Do the hardware assembly such connecting the encoder to the X-axis to read the motor position and connect the reading current circuit we made to the A4988 stepper motors driver to get data.
- Programme the STM32 to do the following tasks:
 - 1- Read the current value from the circuit.
 - 2- Reduce the reading current noise.
 - 3- Count the encoder pulses and stepper motor steps.
 - 4- Send signal to the Arduino to hold and resume X-axis.
 - 5- Send stepper motor and encoder data through serial port and read commands.
- Create a windows form application to do the following:
 - 1- Interfacing between STM32 and Arduino.
 - 2- Draw the current graph shape in real time.
 - 3- Hold the X-axe in case of detecting lost in steps of stepper motor and save the data in form of image and CSV file.
 - 4- Train and test Neural Network model.

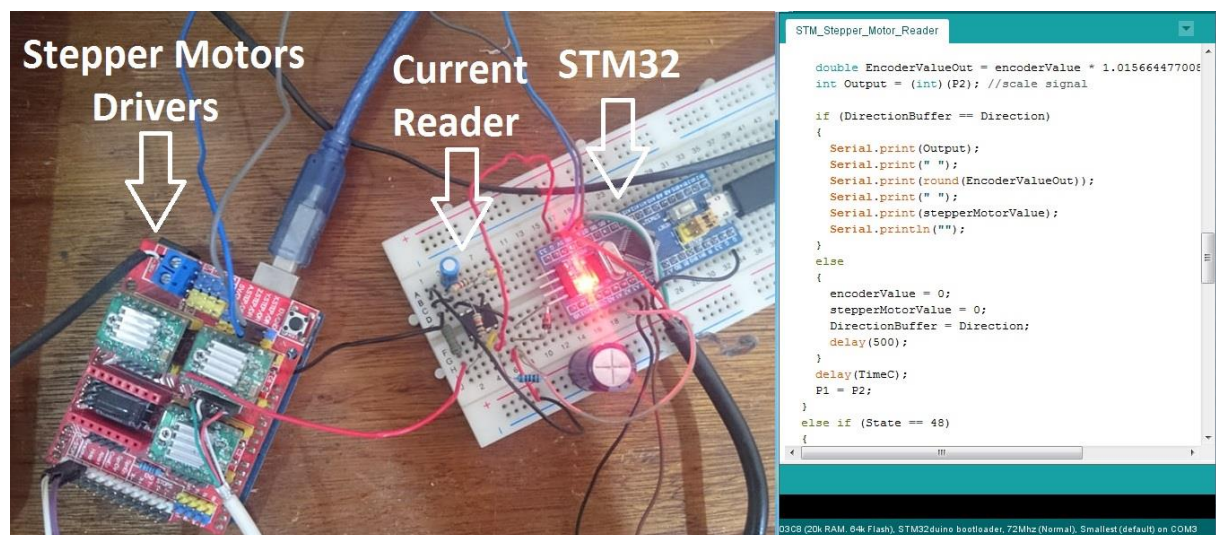


Figure II.13: Test the circuit setup and STM32 code.

Now we run the X-axis in relatively high speed then apply a random force on it until we detect losing steps in the stepper motor. In this point the machine will stop automatically and we get the current shape of last second with step interval of 5 ms like it's shown below. We care about the current shape not its value, because when we run the stepper motor it generates heat and that effect the characteristic of the motor, therefor the current will not be stable.

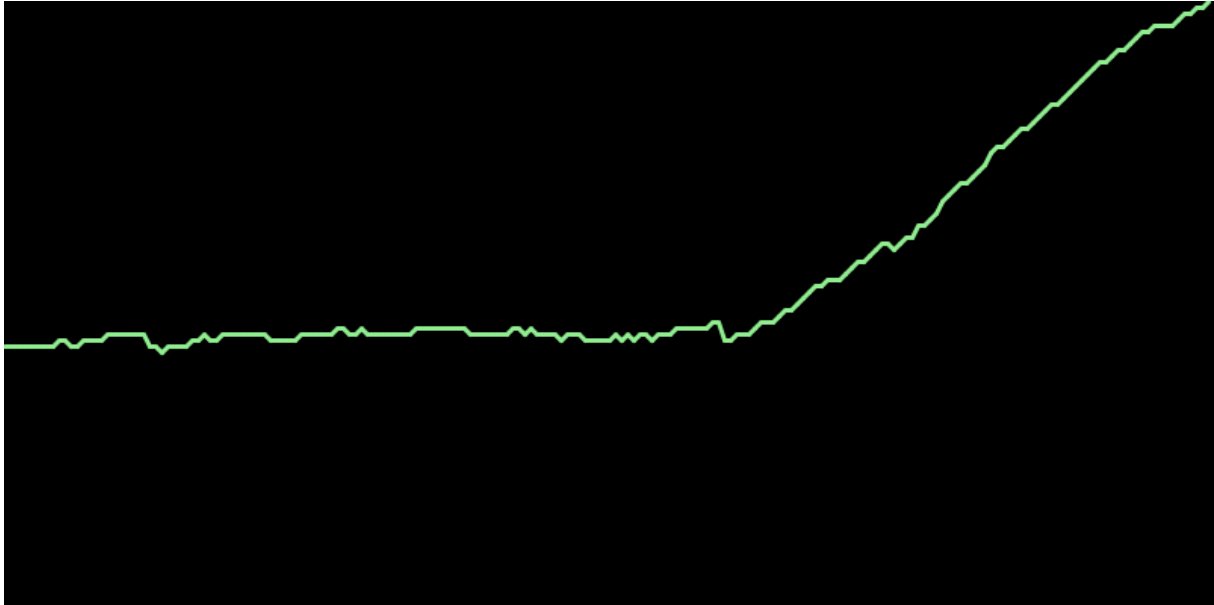


Figure II.14: Current shape of 1 second after steps lose.

We repeat this process as much as possible and collect the data.

Next we run the machine again but this time we don't apply any force (we let it run freely) and collect the data again.

After getting the data, we create our neural network model for CNC machine. The first trial is achieved with 200 input neurons, one hidden layer of 10 neurons and one neuron in output layer. This first training trial was not successful, because the 200 input neurons make the model so much sensitive for any small change in the current shape. Therefore, we will need to collect a huge amount of data and it's impossible to do that manually. The solution is to reduce the number of input neurons and to make the model less sensitive at this point. We decide to try 10 neurons in input layer, one hidden layer with 5 neurons and one neuron in output layer. To decrease the number of inputs to 10 neurons, we take an average of every 100ms from the data we collected, and we get 10 values representing the current shape.

The training process is repeated again, but now with applying a high external force then the motor can handle, the Neural Network stop the machine before it makes an error.

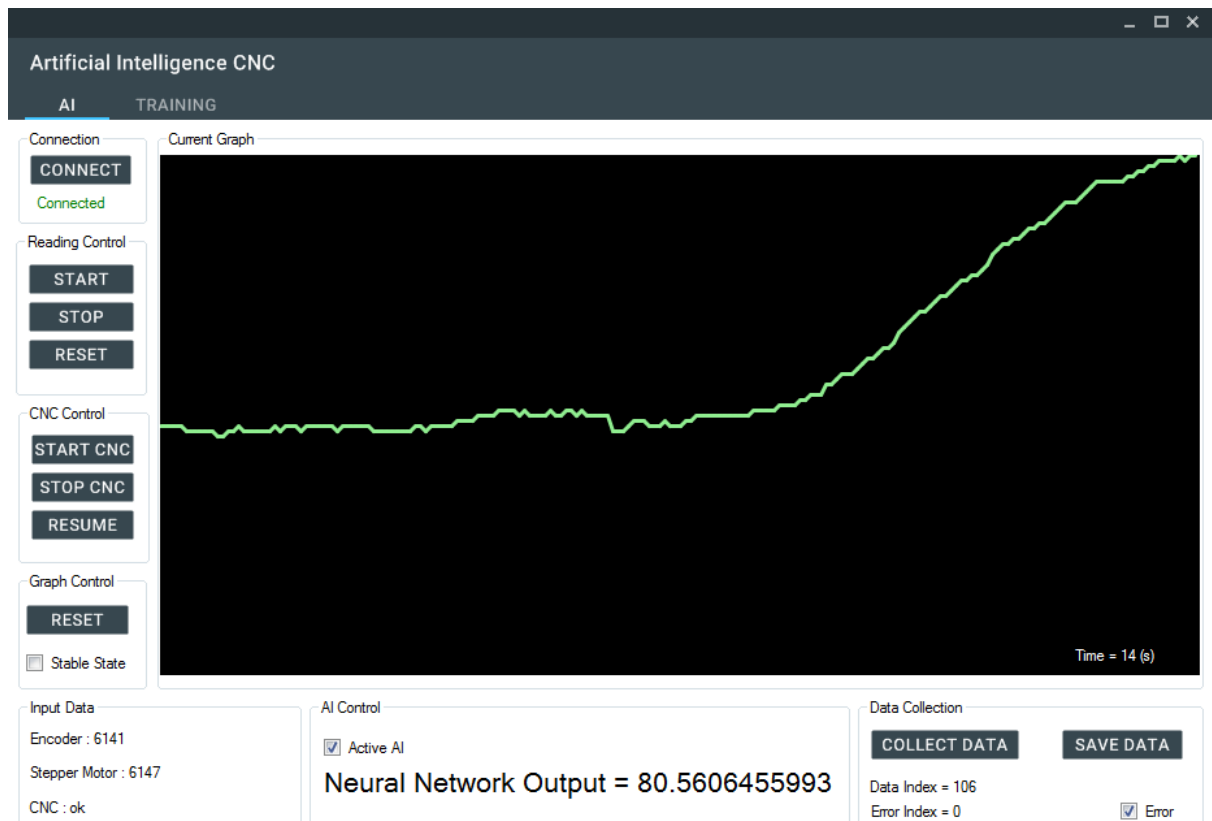


Figure II.15: Artificial intelligence application demo.

II.10 Conclusion

Working with Artificial Neural Network was challenge to us, from being able to create our own MLP library, to test it with real-time OCR and apply it in our CNC Machine.

Neural Network requires other algorithms to work properly. Due to the small dataset for training the CNC Machine, we reduce the number of input neurons to avoid overfitting problem, therefore, our model could predict errors and stop the machine.

Chapter III

Electronics

III.1 Stepper motors

III.1.1 Definition of a stepper motor

Stepper motors are DC motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". By energizing each phase in sequence, the motor will rotate, one step at a time. With a computer controlled stepping you can achieve very precise positioning and/or speed control. For this reason, stepper motors are the motor of choice for many precision motion control applications.

Stepper motors are used for their high working ability and precision level such as the one we are building for our CNC machines project. Unlike DC motors, the stepper motors are brushless, synchronous electric motors that can divide a full in both directions. It has a capability of holding torque at zero speed, and precise digital control without any feedback system depending on the overall size of the project and application. The stepper motors are constant power devices. As speed increases the torque decreases, so we will have to try to find a happy medium for the need to drive our CNC machine. Stepper motors come in different types and multiple coil winding. Unipolar stepper motors are such types of motors, which are easy to drive, and having comparatively low torque and speed, on the other hand bipolar motors are hard to drive but have high torque and high speed. We are looking for a motor with high speed and high precision capabilities and could carry a reasonably sized object-so the bipolar would be a convenient choice. Since we have an available transformer that allows 24V, we will look for that with our motors. We will be using a 2A driver board so the motor should only take 2 amps of current per phase. Micro stepping with 1.8 degrees and 200 steps per revolution would be great for speed and also the precision that we wanted [7].



Figure III.1 Types of stepper Motors

Stepper motors are the most adequate for tasks like precise cutting, plotting, measurement and motion controlling. This is why we used NEMA 17 stepper motor in our machine. they can partition a full turn into a large number of steps. This allows for precise control without any feedback system depending on the size of the project and application. The stepper motors are constant power devices. As speed increases the torque decreases, so we will have to try to find a happy medium for the need to drive our CNC machine. They come in different types, unipolar, which are easy to drive but have low torque and speed, and bipolar which are hard to drive but have high torque and high speed. As we have used NEMA 17 stepper motor which is high in speed and precision capabilities. The load capacity of this motor 5.6lbs or 2.5kgs approximately.

III.1.2 Characteristics

1.2.1 *Holding Torque*

Stepper motors have very good low speed and holding torque. They are usually rated in terms of their holding force and can even hold a position (to a lesser degree) without power applied, using magnetic 'detent' torque.

1.2.2 *Open loop positioning*

Perhaps the most valuable and interesting feature of a stepper motor is the ability to position the shaft in fine predictable increments, without need to query the motor as to its position. Stepper motors can run 'open-loop' without the need for any kind of encoder to determine the shaft position. Closed loop systems that feedback position information, are known as servo systems. Compared to servos, stepper motors are very easy to control; the position of the shaft is guaranteed as long as the torque of the motor is sufficient for the load, under all its operating conditions.

1.2.3 *Load Independent*

The rotation speed of a stepper motor is independent of load, provided it has sufficient torque to overcome slipping. The higher rpm a stepper motor is driven, the more torque it needs, so all steppers eventually poop out at some rpm and start slipping. Slipping is usually a disaster for steppers, because the position of the shaft becomes unknown. For this reason, software usually keeps the stepping rate within a maximum top rate. In applications where a known rpm is needed under a varying load, steppers can be very handy.

III.1.3 Types of Stepper Motors

1.3.1 *Permanent Magnet Motor*

- **Magnetic Rotor:** The permanent magnet type of stepper motor has the characteristic magnetized rotor.
- **Greater resolution as pole pairs increase:** we can improve the resolution of rotor rotation, or decrease the step angle in a permanent magnet rotor by either increasing the number of pole pairs on the rotor itself.

- **Additional Phases:** We could also increase the resolution by adding more stators and phases. We can also increase the resolution in a third way using different stepping techniques.
- **Rotor rotates by energizing each winding:** Current flow generates magnetic polarity on each stator. To rotate the rotor, voltage is applied to each phase sequentially, again current begins to flow creating a polarity on each pole of that stator. Rotation in a particular direction is accomplished by applying voltage to the individual phases in a particular sequence. This means that to rotate the rotor in the opposite direction, simply reverse this voltage sequence. To hold the rotor at a particular position, step it to that angle and then stop the sequence maintaining voltage on the appropriate phase.

1.3.2 Variable Reluctance

Non-magnetic rotor made of soft-iron z Greater resolution as more teeth are added. This motor uses a non-magnetized, soft-iron rotor. The rotor here actually has teeth that are carefully offset from the stator poles to accomplish rotation. Notice also that the individual stator windings are configured differently than what we have discussed so far. All windings have a common terminal that will be connected to a voltage source. The opposite end of each winding is kept separate from the other windings. To increase the resolution on this type of motor, typically more teeth are added to the geared rotor.

III.2 Motor driver

III.2.1 Unipolar drive circuit

A simple unipolar drive circuit suitable for use with a three-phase variable-reluctance stepping motor is shown. Each phase winding is excited by a separate drive circuit, which is controlled by a low-power 'phase control signal'. The phase winding is excited whenever a sufficiently high base current saturates its switching transistor. Under these conditions the full dc supply voltage is applied across the series combination of phase winding and forcing resistance, since the voltage drop across the saturated transistor is small (typically 0.2 V). The dc supply voltage (V_S) is chosen so that it produces the rated winding current (I) when applied to the total phase circuit resistance, which is equal to the sum of the phase [8].

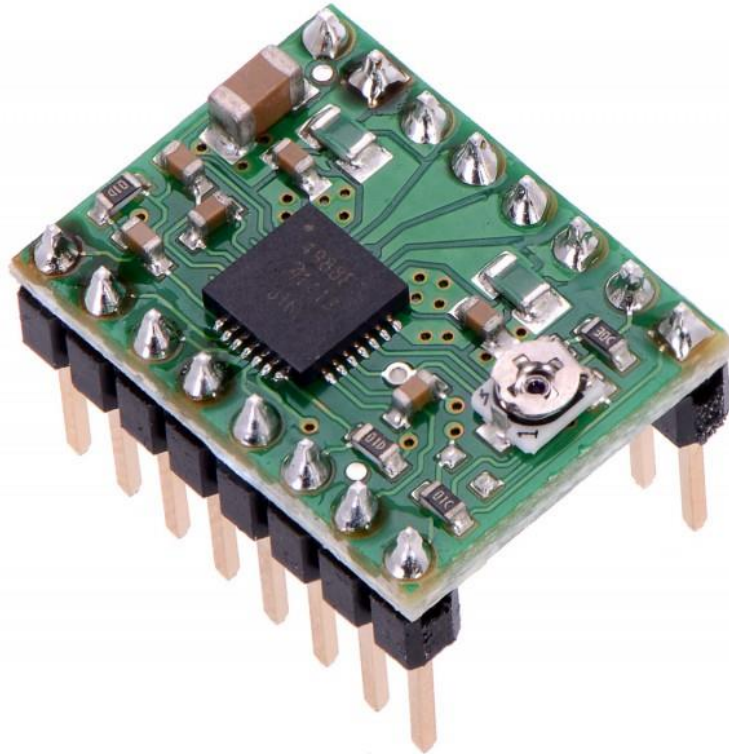


Figure III.2 A4988 pololu circuit driver.

III.2.2 Bipolar drive circuit

One phase of a transistor bridge bipolar drive circuit, suitable for use with a hybrid or permanent-magnet stepping motor, is shown in Fig. 2.2. The transistors are switched in pairs according to the current polarity required. For positive excitation of the phase winding, transistors T1 and T4 are turned on, so that the current path is from the supply, through transistor T1 to the phase winding and forcing resistance, then through transistor T4 back to the supply. In the opposite case the transistors T2 and T3 are turned on so that the current direction in the phase winding is reversed.

The four switching transistors in the bridge require separate base drives to amplify the two (positive and negative) phase control signals. In the case of the 'upper' transistors (T1 and T2) the base drive must be referred to the positive supply rail, which may be at a variable potential. For this reason the phase control signals to these upper base drives are often transmitted via a stage of optical isolation. A bridge of four diodes, connected in reverse parallel with the switching transistors, provides the path for freewheeling currents. In the illustration of Fig. 2.2 the freewheeling current path, via diodes D2 and D3, corresponds to the situation immediately after turn-off of transistors T1 and T4. The freewheeling path includes the dc supply and therefore some of the energy stored in the phase winding inductance at turn-off is returned to the supply. The consequent improvement in overall system efficiency represents a significant advantage of the bipolar bridge drive over the unipolar drive. For this reason most large (>1 kW) stepping motors, including variable-reluctance types, are operated from circuits which allow stored magnetic energy to be returned to the supply. Freewheeling currents in the bipolar drive decay

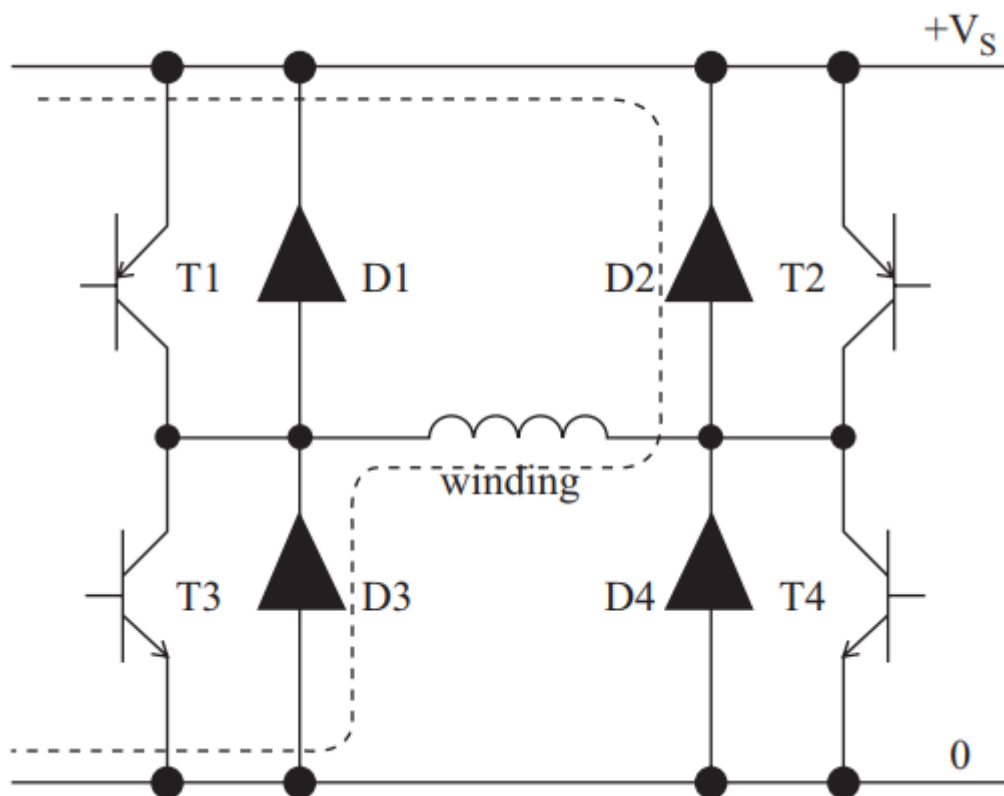


Figure III.3 One phase of a transistor bridge bipolar drive circuit [8].

more rapidly than in the unipolar drive, because the dc supply voltage opposes them. Therefore it is not necessary to include additional freewheeling resistance in the bipolar bridge drive [8].

III.2.3 Micro-stepping

Microstepping is a method of controlling stepper motors, typically used to achieve higher resolution and smoother motion at low speeds.

Microstepping control divides each full step into smaller steps to help smooth out the motor's rotation, especially at slow speeds. For example, a 1.8-degree step can be divided up to 256 times or more, providing a step angle of 0.007 degrees ($1.8 \div 256$), or 51,200 microsteps per revolution.

Microstepping is achieved by using pulse-width modulated (PWM). The driver sends two voltage sine waves, 90 degrees out of phase, to the motor windings. While current increases in one winding, it decreases in the other winding. This gradual transfer of current results in smoother motion and more consistent torque production than full- or half-step control.

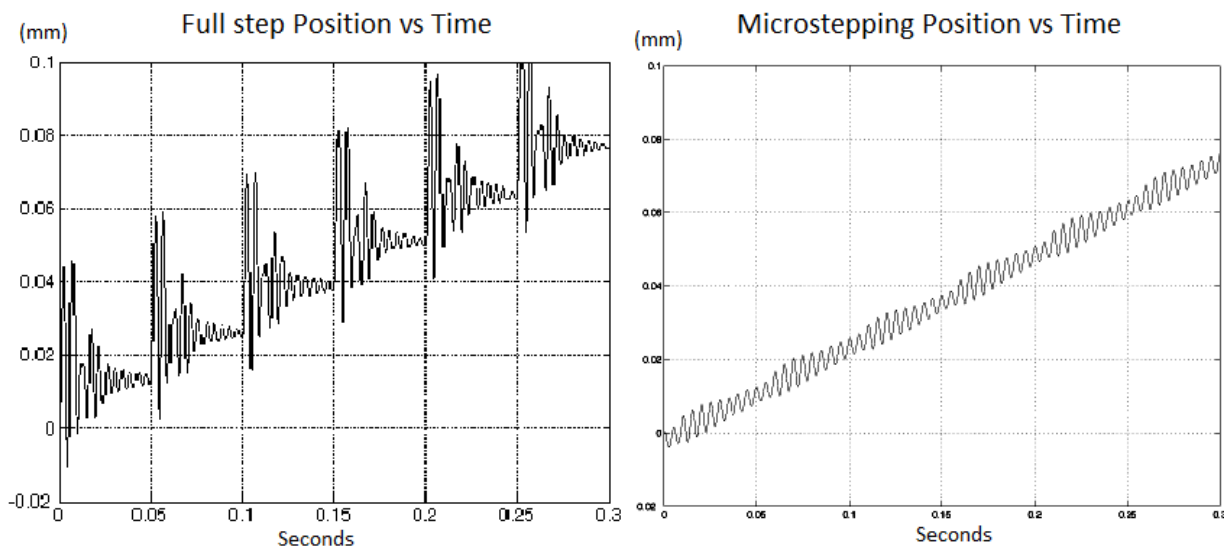


Figure II.4 Full step and Microstepping Position.

III.3 Arduino Board

III.3.1 Definition

Arduino is an open source programmable circuit board that can be integrated into a wide variety of makers projects both simple and complex. This board contains a microcontroller, which is able to be programmed to sense and control objects in the physical world. By responding to sensors and inputs, the Arduino is able to interact with a large array of outputs such as LEDs, motors and displays. Because of its flexibility and low cost, Arduino

has become a very popular choice for makers and makerspaces looking to create interactive hardware projects. Arduino was introduced back in 2005 in Italy by “Massimo Banzi” as a way for non-engineers to have access to a low cost, simple tool for creating hardware projects.

III.3.2 Arduino board types

- Arduino Uno
- Arduino Mega
- Arduino Diecimila
- Arduino NG Rev.C
- Arduino Extreme v2
- Arduino NG 240
- Arduino lily pad
- Arduino Nano
- Arduino Mini
- Arduino Micro

There is more and more open source Arduino Boards but we will not name them all, we chose Arduino Uno R3.

III.3.3 Arduino Uno R3

One of the most popular Arduino boards out there is the Arduino Uno. While it was not actually the first board to be released, it remains to be the most actively used and most widely documented on the market. Because of its extreme popularity, the Arduino Uno has a ton of project tutorials and forums around the web that can help you get started or out of a jam. We are big fans of the Uno because of its great features and ease of use.

3.3.1 *The brain ATmega328 microcontroller chip*

You can think of the microcontroller chip itself as the “brains” of the board. The chip used in the Arduino Uno is the ATmega328, made by Atmel. It’s the large, black component in the center of the board. This chip is known as an integrated circuit, or IC. It’s actually not alone but rather sits in a socket. If you were to remove it [9].



Figure III.5: Atmel Atmega328P

The microcontroller socket connects all the legs of the ATmega328 microcontroller chip to other sockets, referred to as header sockets, which have been arranged around the board and labeled for ease of use. They are the black sockets that go around the edge of the Arduino board. These are divided up into three main groups: digital pins, analog input pins, and power pins. All these pins transfer a voltage, which can either be sent as output or received as an input. Why are these pins important? They allow additional circuitry to be connected to the board quickly and easily when prototyping with a breadboard and allow additional boards, called shields, to be designed that will fit neatly on top of your Arduino board. This same process of sending and receiving electrical signals is going on inside modern computers, but because they are so advanced and refined compared to a humble Arduino, it is difficult to directly link a computer that is accustomed to digital signals (0s and 1s) to an electronic circuit that deals with a range of voltages (in the ATmega328’s case 0v to 5v) [9].

3.3.2 Board details

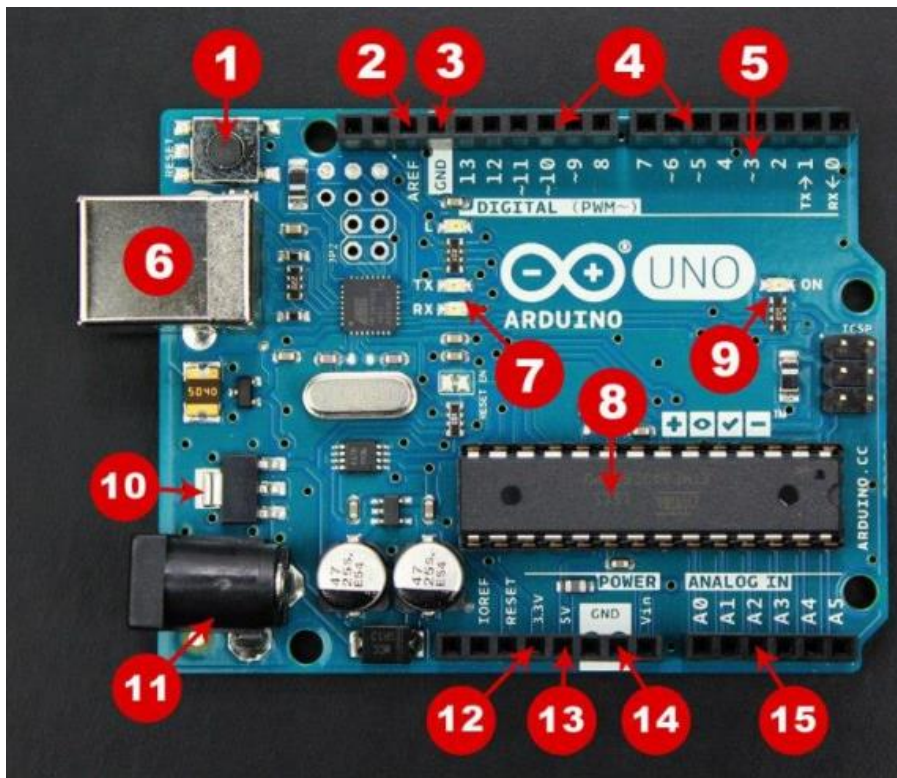


Figure III.6: Arduino Uno

1. **Reset Button** – This will restart any code that is loaded to the Arduino board.
2. **AREF** – Stands for “Analog Reference” and is used to set an external reference voltage.
3. **Ground Pin** – There are a few ground pins on the Arduino and they all work the same.
4. **Digital Input/Output** – Pins 0-13 can be used for digital input or output.
5. **PWM** – The pins marked with the (~) symbol can simulate analog output.
6. **USB Connection** – Used for powering up your Arduino and uploading sketches.
7. **TX/RX** – Transmit and receive data indication LEDs.
8. **ATmega Microcontroller** – This is the brains and is where the programs are stored.
9. **Power LED Indicator** – This LED lights up anytime the board is plugged in a power source.
10. **Voltage Regulator** – This controls the amount of voltage going into the Arduino board.
11. **DC Power Barrel Jack** – This is used for powering your Arduino with a power supply.
12. **3.3V Pin** – This pin supplies 3.3 volts of power to your projects.
13. **5V Pin** – This pin supplies 5 volts of power to your projects.

14. **Ground Pins** – There are a few ground pins on the Arduino and they all work the same.

15. **Analog Pins** – These pins can read the signal from an analog sensor and convert it to digital.

3.3.3 Arduino IDE

Once the circuit has been created on the breadboard, you will need to upload the program (known as a sketch) to the Arduino. The sketch is a set of instructions that tells the board what functions it needs to perform. An Arduino board can only hold and perform one sketch at a time. The software used to create Arduino sketches is called the IDE which stands for Integrated Development Environment.

The sketch is written in C Arduino language, that's derived from C/C++ language.

Every Arduino sketch has two main functions to the program: **Void setup ()** – Sets things up

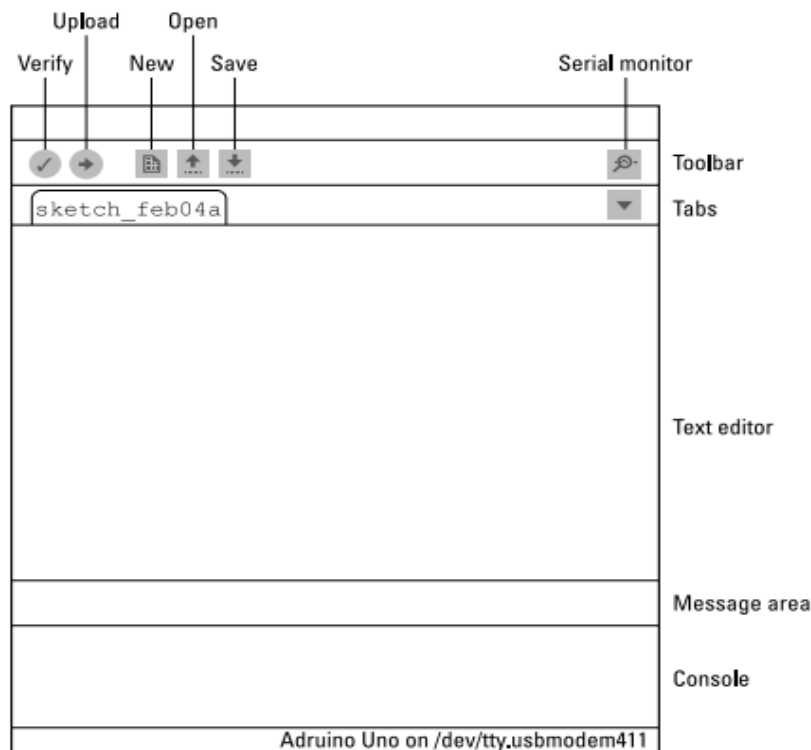


Figure III.7 : Arduino IDE Platform

that have to be done once and then do not happen again. **Void loop ()** – Contains the instructions that are repeated over and over until the board is turned off.

III.4 Motion sensors (end stops)

All CNC Machines needs a an end-stop (also known as home position) to reference their movements. At the start of each build, each axis needs to back up until the datum point is reached. The switches also help protect the machine from moving past its intended range and damaging itself.

III.4.1 Types of end-stops

4.1.1 Mechanical end-stop

Precision/repeatability depends on the switch quality, length of lever arm attached (longer increases contact distance but is worse for precision), and impact speed of the carriage with the switch. It is possible to have a good mechanical switch or a bad mechanical switch. This is typically a reasonable default choice because it is simple and cheap.



Figure III.8 : Mechanical end-stop

A small mechanical switch with a short lever arm (or the lever arm removed) will generally achieve the required $\pm 0.01\text{mm}$ switching precision. Very cheap switches, high contact speeds, and long lever arms may provide inadequate resolution for Z homing or probing, but will still be adequate for low-precision X and Y homing purposes.

Where mechanical switches tend to cause issues is in noise rejection. Different controller boards use different ways of wiring the switch: some use two wires and only send a signal when triggered. When not triggered, the signal wire is left floating or weakly pulled up by the

microcontroller, while attached to a long wire that acts as an antenna to pick up EM noise. It is very common for heater or stepper wiring to emit nasty EMR due to the PWM current control. Two-wire end-stop cables should always be run away from stepper and heater wiring. Shielding and twisting the conductors is a good idea too.

A more robust approach is to use three-wire switches that actively pull the signal line high or low depending on the switch position. These will tend to reject noise better.

Very cheap mechanical switches may fail within the life of the printer. However, most limit switches are rated for millions of cycles, which is unlikely to occur over any normal printer's lifespan.

Mechanical switches are easy to align and easy to trigger by hand during troubleshooting.

4.1.2 *Optical end-stop*

These rely on a flag blocking a window between a light emitter and a detector. This is non-contact and can be quite reliable, but introduces some challenges. The exact trigger position (and thus precision) may depend on ambient light levels in the room, because the sensor is monitoring for light to decrease below a specific intensity. So it may be very repeatable/precise in the short term but have some drift if the sensor moves in and out of the sun through the day.

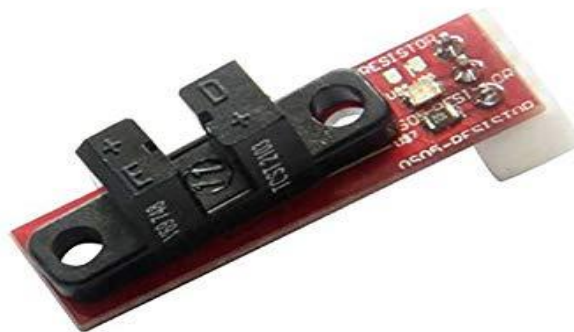


Figure III.9: Optical end-stop.

Switching tends to be more consistent and reliable if the flag enters the window from the side, rather than the top.

Optical switches will actively pull the signal line high or low, and thus have good electrical noise rejection.

4.1.3 Magnetic end-stop

These measure the intensity of the nearby magnetic field and trigger when it exceeds a certain amount in a certain polarity. This is highly precise/repeatable (better than +/-0.01mm) and extremely resistant to noise and environmental conditions. (Unless your printer is next to something that emits large magnetic fields, anyway.)

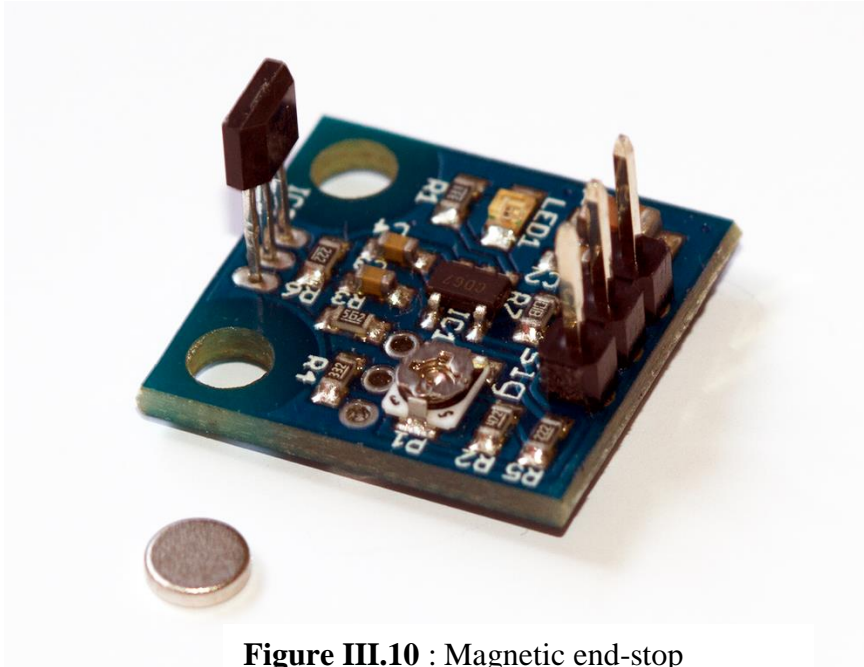


Figure III.10 : Magnetic end-stop

The hall switches I've seen have an adjustable trim pot to tune the trigger distance. That's a nice feature when trying to manually calibrate a Delta or a Z-bed for first layer height.

The primary downside to hall switches is that they need a magnet to trigger the switch. This can be difficult to trigger by hand during troubleshooting, and requires attaching a magnet somewhere on the moving carriage. Glue works fine... but do not glue the magnet in place backwards.

III.5 Encoders

Simply put, an encoder is a sensing device that provides feedback. Encoders convert motion to an electrical signal that can be read by some type of control device in a motion control system, such as a counter or PLC. The encoder sends a feedback signal that can be used to determine position, count, speed, or direction. A control device can use this information to send a command for a particular function. For example:

- In a cut-to-length application, an encoder with a measuring wheel tells the control device how much material has been fed, so the control device knows when to cut.
- In an observatory, the encoders tell actuators what position a moveable mirror is in by providing positioning feedback.
- On railroad-car lifting jacks, precision-motion feedback is provided by encoders, so the jacks lift in unison.



Figure III.11 : Rotary encoder.

- In a precision servo label application system, the encoder signal is used by the PLC to control the timing and speed of bottle rotation.
- In a printing application, feedback from the encoder activates a print head to create a mark at a specific location.
- With a large crane, encoders mounted to a motor shaft provide positioning feedback so the crane knows when to pick up or release its load.
- In an application where bottles or jars are being filled, feedback tells the filling machines the position of the containers.
- In an elevator, encoders tell the controller when the car has reached the correct floor, in the correct position. That is, encoder motion feedback to the elevator's controller ensures that elevator doors open level with the floor. Without encoders, you might find yourself climbing in or out of an elevator, rather than simply walking out onto a level floor.

- On automated assembly lines, encoders give motion feedback to robots. On an automotive assembly line, this might mean ensuring the robotic welding arms have the correct information to weld in the correct locations.

In any application, the process is the same: a count is generated by the encoder and sent to the controller, which then sends a signal to the machine to perform a function.

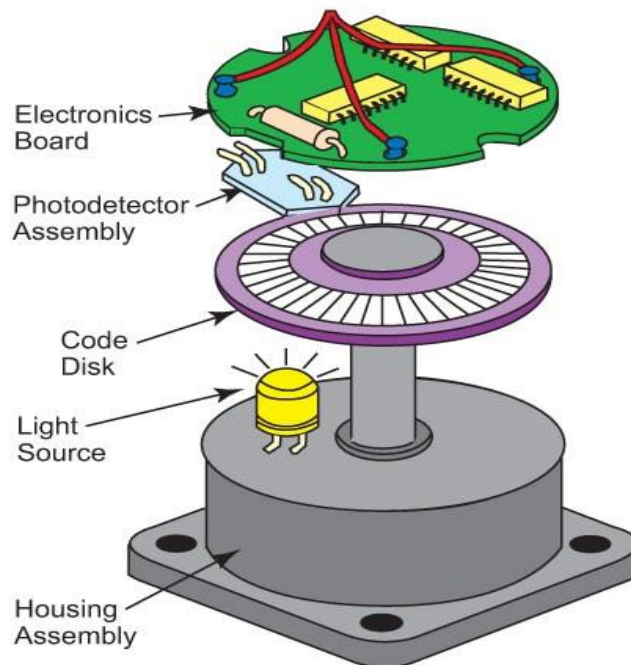


Figure III.12: Encoder schematics.

III.5.1 How encoders work ?

Encoders use different types of technologies to create a signal, including mechanical, magnetic, resistive and optical – optical being the most common. In optical sensing, the encoder provides feedback based on the interruption of light.

The graphic at right outlines the basic construction of an incremental rotary encoder using optical technology. A beam of light emitted from an LED passes through the Code Disk, which is patterned with opaque lines (much like the spokes on a bike wheel). As the encoder shaft rotates, the opaque lines on the Code Disk interrupt the light beam from the LED before being picked up by the Photodetector Assembly. This produces a pulse signal: light = on; no light =

off. The signal is sent to the counter or controller, which will then send the signal to produce the desired function.

III.6 Router motor

Self-Contained Spindles, especially Trim Routers, are very popular with the DIY CNC Router crowd. There's a lot to like about a unit like the Makita RT0701CR pictured above:

- 1.25 HP: That's plenty of power for the scale machine and frame stiffness you're likely to achieve in a DIY CNC project.
- 10,000 to 30,000 rpm speed range is pretty broad.
- Easily mounted with a simple spindle clamp. You can even mount one on the side of an existing spindle to pick up a higher rpm range.

There are downsides too:

- The toolholder is not removable. The spindle has a collet that usually only accepts 1 size tool shank and there's no quick change tool holders. Manual tool changes are pretty slow and you can forget automatic tool changers.
- Routers and similar spindles can be really noisy, though that isn't universal.

The CNC spindle is the heart of any mill. It consists of a rotating assembly with a taper where tool holders may be installed.

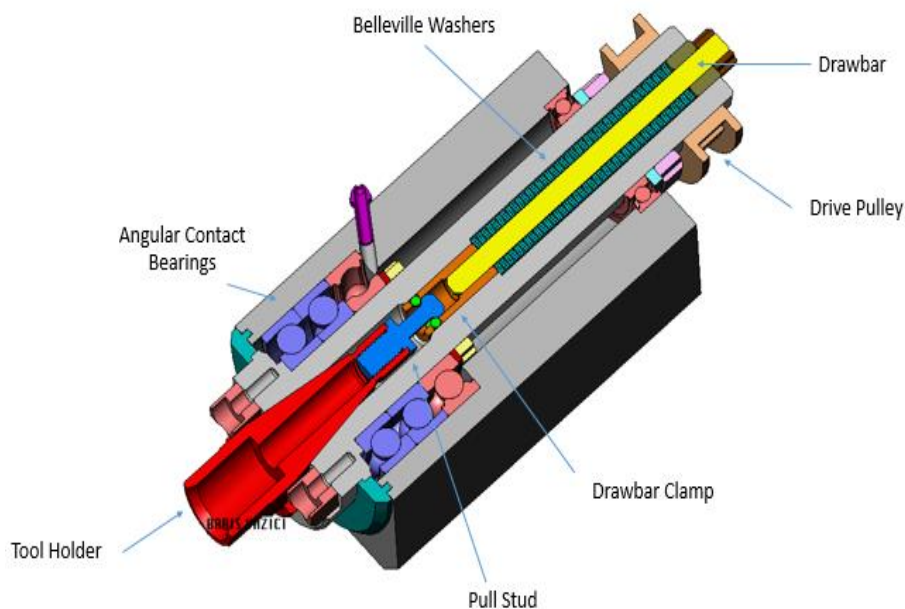


Figure III.13: CNC ATC Cartridge Spindle

A CNC spindle motor with optional transmission of some kind rotates the CNC spindle. The transmission matches the highest power rpm range of the CNC spindle motor to the spindle rpms that are ideal for the particular speeds and feeds of the material being cut.

Spindles come in three types. There are cartridge spindles that are just the rotating assembly without motor or transmission. Then there are self-contained spindles of various kinds. For example, Trim Routers are popular with the DIY CNC crowd, especially for CNC Routers.

Self-contained spindles incorporate the rotating assembly and motor all-in-one. Lastly, there are fabricated spindles where the parts such as the spindle bearings are fitted to a (typically) cast iron housing. That's the sort of construction used in a Bridgeport milling machine or many Chinese Import machines such as the RF-45, for example.

Cartridge Spindles are what pretty much every modern VMC (vertical machining center) uses. They're convenient to swap out and rebuild while keeping the machine going, they're more convenient to manufacture than fabricated spindles, and they generally just work well.

Here's a cutaway of a cartridge spindle set up for ATC (Automatic Tool Changer) so you can get an idea of the components.

Let's go over the role of each component:

- **Angular Contact Bearings:** This particular spindle has two angular contact bearings plus two deep groove ball bearings (salmon colored). The bearings can be the most important part of the spindle and determine its maximum rpm as well as its rigidity and suitability for CNC.
- **Drawbar:** The Drawbar is used to "draw" the Tool Holder up into the Spindle Taper, hence the name.
- **Belleville Washers:** These are a type of flat spring whose purpose is to keep the drawbar's tension on the tool holder.
- **Pull Stud:** This is a replaceable part that screws into the tool holder. The Drawbar Clamp grabs the pull stud so the Drawbar can pull it up into the Taper.
- **Drawbar Clamp:** There are different designs, but the Drawbar Clamp locks the Drawbar onto the Pull Stud when it has brought the Stud far enough up into the Taper.
- **Drive Pulley:** The motor or transmission rotate the spindle via the Drive Pulley. The design shown is a timing pulley, but many styles are available.

Ambitious DIY CNC'ers can design and manufacture their own spindle cartridges, but it is much easier to buy one. There are high-quality (at least for the DIY market) cartridges available at reasonable prices from outfits like Tormach.

We can even find used cartridge spindles from VMCs in places like eBay. Just be aware that if they are not in good condition, the bearings alone for a commercial VMC are very expensive to replace. If the taper is damaged or there is excessive wear requiring re-machining.

III.6.1 Self-Contained Spindles



Figure III.14: Makita Trim Router: 1 1/4 HP high rpm spindle

Self-Contained Spindles, especially Trim Routers, are very popular with the DIY CNC Router crowd. There is a lot to like about a unit

- 1.25 HP: That is plenty of power for the scale machine and frame stiffness you are likely to achieve in a DIY CNC project.
- 10,000 to 30,000 rpm speed range is broad.
- Easily mounted with a simple spindle clamp. You can even mount one on the side of an existing spindle to pick up a higher rpm range.

There are downsides too:

- The toolholder is not removable. The spindle has a collet that usually only accepts 1 size tool shank and there's no quick change tool holders. Manual tool changes are pretty slow and you can forget automatic tool changers.

- Routers and similar spindles can be noisy, though that is not universal.

III.6.2 Fabricated Spindles

In older design manual milling machines, we often find what we are calling “Fabricated Spindles”. These spindles are the hardest to work with and modify as they are little built right into the spindle head casting and do not allow much room for modification.

With that said, a common approach is to at least clamp down movable quills for greater rigidity. Another common modification is a conversion from gears (really noisy and slow!) to belt drive.

III.6.3 DIY CNC Spindle Selection

Proper selection of a spindle for your DIY CNC project begins with drawing up a set of scenarios for how we want to use the machine. It is important to understand a number of decisions in making the decision:

- What materials do we intend to cut on the machine? The rpm requirements for hard metals are quite a bit different than for soft materials like wood and plastics.
- What size cutters will you employ?
- Will we eventually need an automatic tool changer? Many decisions will be made around this.

In general, we try to make our choices as much inexpensive off-the-shelf accessories as possible can be used. Rather than choose an exotic spindle taper, we chose something common so we can buy a tool holder cheaply.



Figure III.15: Dramel 3000 spindle.

III.7 Application Part

In our machine, the circuits used are mentioned below:

- Controlling board → Arduino UNO.
- Motors → Nema 17 Stepper Motors.
- Motors driver → A4988 Pololu.
- Router head → Dremel 3000.
- CNC shield → GRBL shield.

III.1.1 Schematics test circuit

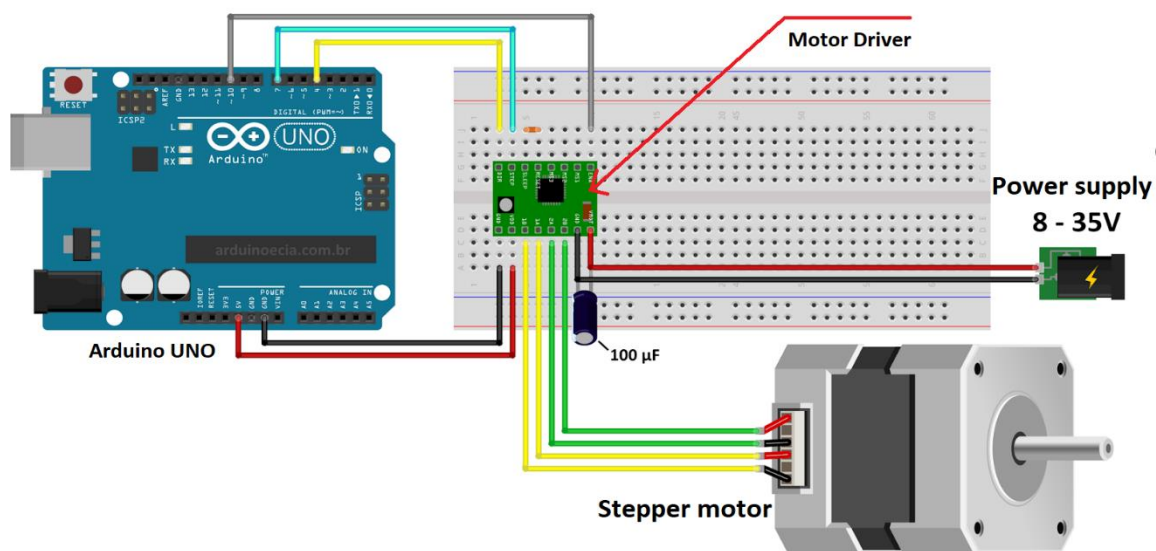


Figure III.16: Schematics of controlling motor circuit.

III.7.1 Back EMF

Back electromotive force (or back EMF), is the electromotive force or "voltage" that opposes the change in current which induced it. CEMF is the EMF caused by magnetic induction (see Faraday's law of induction, electromagnetic induction, Lenz's Law).

For example, the voltage appearing across an inductor or "coil" is due to a change in current which causes a change in the magnetic field within the coil, and therefore the self-induced voltage.[17] The polarity of the voltage at every moment opposes that of the change in applied voltage to keep the current constant [17][18].

III.7.2 Learning circuit

The IC1a (LM358) is operational amplifier in non-inverting mood with gain of 100 calculated in this formula:

$$\text{Gain} = 1 + R1/R2 \quad (\text{III.1})$$

The IC1b (LM358) is used as voltage follower to isolate the output and R3, C1 is RC low pass filter to smooth input voltage.

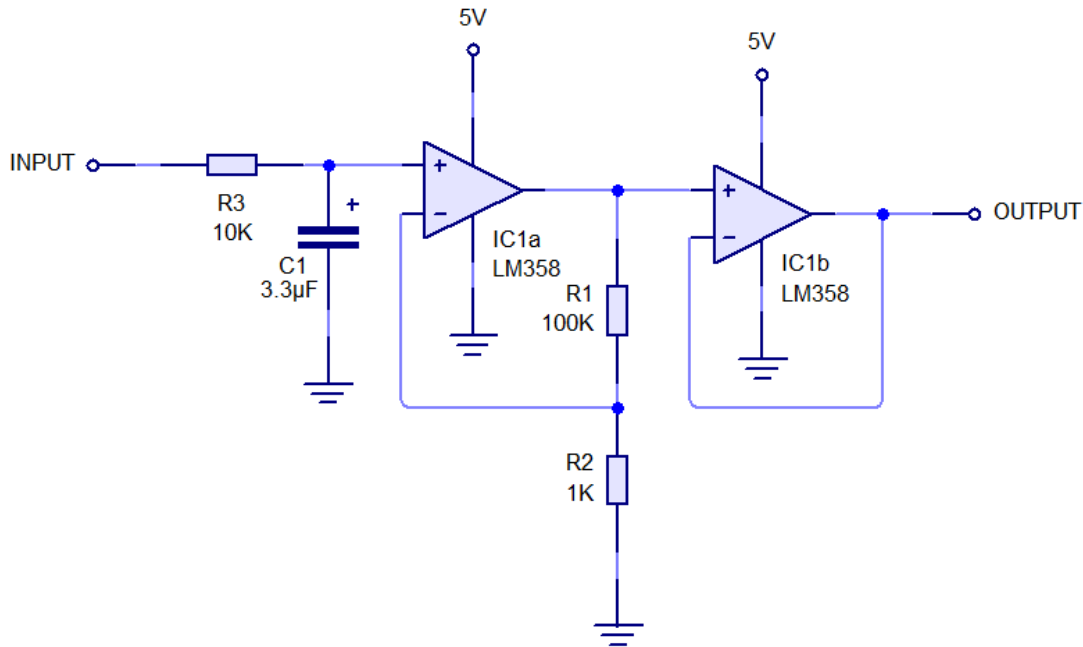


Figure III.17: Filter and amplifier circuit.

III.8 Conclusion

The electronics in CNC machines is what gives life to it, beside it's a huge part after the mechanical part, everything from controlling the motors to making it read collected data. What we can say about this chapter is that reading the current from the stepper motors is possible only if the speed is significantly high and that's due to the Back EMF phenomena.

For most components it's easy for everyone to assemble and build at home with no need to solder any part or circuit, making it easy for people that has no experience dealing with electronics at the first place.

Chapter IV

Mechanical Study

IV.1 Introduction

In this chapter, we are going to study the mechanical aspects of a CNC machine, the important parameters involved, and what we need exactly in order to build a CNC machine.

The overall goal in constructing a CNC router, 3D printer or plasma machine is typically to have the heavy immovable stationary portions to help reduce vibration. Another goal is to have the movable parts be as lightweight as possible (yet strong and stiff enough to handle the intended loads). Thus, faster accelerations will be possible because of lower inertia mass of the movable parts.

IV.2 Type of materials used in CNC machines

Almost any material can be used in a CNC machine. It really depends on the application. Common materials include metals such as aluminium, brass, copper, steel, and titanium, as well as wood, foam, fiberglass, and plastics such as polypropylene.

CNC machining can produce parts from almost any metal or plastic. Due to this wide range of available materials, the selecting the right one for your application can be challenging.

We compare the most common CNC materials, in terms of mechanical and thermal properties, **cost** and typical applications. We summarized the information in easy-to-follow tables and graphs and give you specific details for each available CNC material option.

The basic steps of the material selection process are:

- **Step 1:** Define the material requirements: These can include mechanical, thermal or other material requirements, as well as cost and surface finish. Consider the environment that the part will be used in and the components it will interact with.
- **Step 2:** Identify candidate materials: Pin down a few candidate materials that fulfill all (or most) of your design requirements.
- **Step 3:** Select the most suitable material: A compromise is usually required here between two or more of the design requirements (for example, mechanical performance and cost).

IV.2.1 CNC materials selection guidelines

Metal and plastic materials were grouped together and compared with each other, as their properties differ greatly. Metals are mainly used in applications that require high strength, hardness, and thermal resistance. Plastics are lightweight materials with a wide range of physical properties, often used for their chemical resistance and electrical insulation properties.

The materials properties of interest are the mechanical strength (expressed as tensile yield strength), the machinability (the ease of machining affects CNC pricing), the material **cost**, the hardness (mainly for metals) and the temperature resistance (mainly for plastics). The gathered information are summarized in the tables below. A detailed description of each material option is given in the next section.

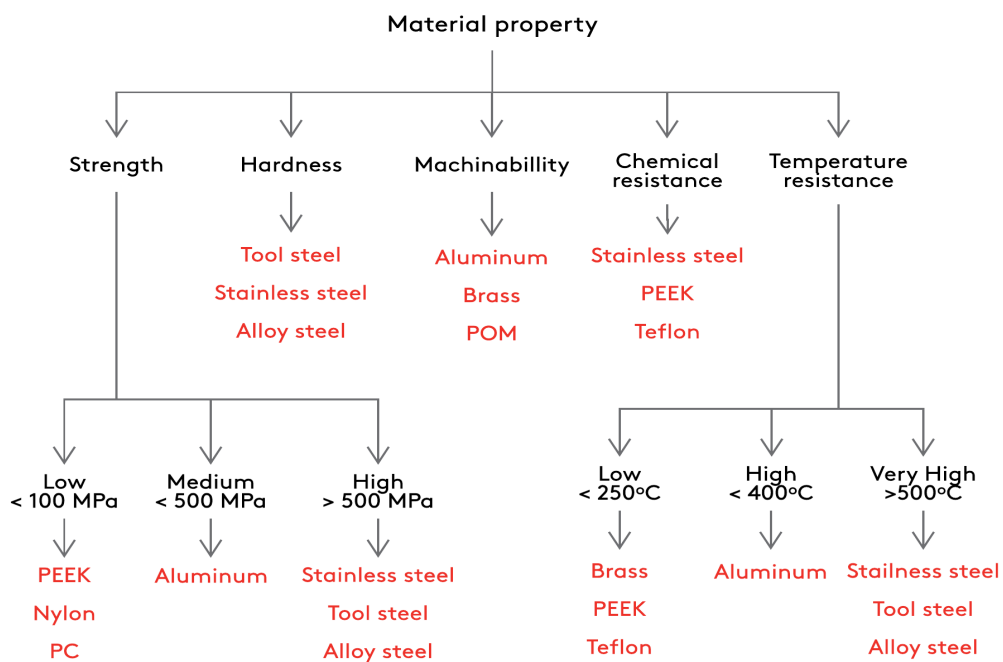


Figure IV.1: Infographic reference to quickly identify CNC

IV.2.2 Summary table for metals

Metal	Grade	Strength	Hardness	Machinability	Cost	Typical Applications
Aluminum	6061	Medium	Medium	★★★★★	\$	General purpose Aircraft components Automotive parts Bicycle frames Food containers
Stainless steel	304	High	Medium	★★	\$\$\$	General purpose Medical devices Food industry Marine applications Chemical processing
Mild steel	1018	Medium	Medium	★★★	\$\$	General purpose Machinery parts Jigs & fixtures
Alloy steel	4140	Medium	High	★★	\$\$\$	General purpose Machinery parts Tooling
Tool steel	D2	High	Very High	★	\$\$\$\$	Cold-working tooling Dies & stamps Cutting tools & knives
Brass	C36000	Medium	Medium	★★★★★	\$\$	Mechanical parts Valves & nozzles Architecture

Table VI.1: Summary table for metals.

IV.2.3 Overview of common CNC metal alloys

2.3.1 Aluminium alloys

Aluminium alloys have an excellent strength-to-weight ratio, a high thermal and electrical conductivity and natural protection against corrosion. They can be easily machined and have a low bulk cost, so they are often the most economical option of creating custom metal parts and prototypes.

Aluminum alloys typically have a lower strength and hardness than steels, but they can be anodized, creating a hard, protective layer on their surface.



Figure VI.2: Aluminium 6061 part.

Aluminum 6061 is the most common, general-use aluminum alloy, with good strength-to-weight ratio and excellent machinability.

Aluminum 6082 has similar composition and material properties to 6061. It is more commonly used in Europe, as it is compliant with British Standards.

Aluminum 7075 is the alloy most commonly used in aerospace applications where weight reduction is critical, as it has excellent fatigue properties and can be [heat treated](#) to high strength and hardness, comparable to steels.

Aluminum 5083 has higher strength than most other aluminum alloys and exceptional resistance to seawater, so it is commonly used for construction and marine applications. It is also an excellent choice for welding.

Material characteristics:

- Typical density of aluminum alloys: 2.65-2.80 g/cm³
- Can be anodized

- Non-magnetic

2.3.2 *Stainless steel*

Stainless steel alloys have high strength, high ductility, excellent wear and corrosion resistance and can be easily welded, machined and polished. Depending on their composition, they can be either (essentially) non-magnetic or magnetic.

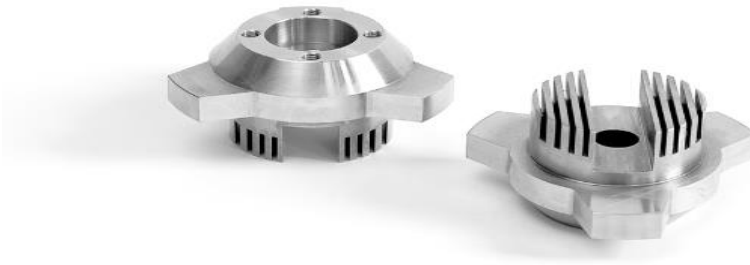


Figure VI.3: Stainless steel 304 part.

Stainless steel 304 is the most common stainless steel alloy and has excellent mechanical properties and good machinability. It is resistant to most environmental conditions and corrosive media.

Stainless steel 316 is another common stainless steel alloy with similar mechanical properties to 304. It has a higher corrosion and chemical resistance though, especially to saline solutions (for example seawater), so it is often preferred for applications in harsh environments.

Stainless steel 2205 Duplex is the stainless steel alloy with the highest strength (double than other common stainless steel alloys) and has excellent resistance to corrosion. It is used in severe environments, with many applications in the Oil & Gas industry.

Stainless steel 303 has excellent toughness, but lower corrosion resistance compared to 304. Due to its excellent machinability, it is often used in high-volume applications, such as the manufacturing of nuts and bolts for aerospace applications.

Stainless steel 17-4 (SAE grade 630) has mechanical properties comparable to 304. It can be precipitation hardened to a very high degree (comparable to tool steels) and has excellent chemical resistance, making it suitable for very high-performance applications, such as the manufacturing of turbine blades.

Material characteristics:

- **Typical density:** 7.7-8.0 g/cm³
- **Non-magnetic** stainless steel alloys: 304, 316, 303
- **Magnetic** stainless steel alloys: 2205 Duplex, 17-4

IV.3 Machine structure

The machine structure is the load carrying and supporting member of the machine tool. All motors, drive mechanisms and other functional assemblies of machine tool are aligned to each other and rigidly fixed to the machine structure. The machine structure is subjected to static and dynamic forces. It is essential that the structure does not deform or vibrate beyond the permissible limits under the action of these forces. All the parts of the machine must remain in correct relative relationship to maintain the geometric accuracy regardless of magnitude and direction of these forces. The machine structure configuration is also influenced by the requirements of the manufacture, assembly and operation.

The basic design factors involved in the design of a machine structure are given below.

IV.3.1 Static Load

The static load of a machine tool results from the weights of slides and the job, and the forces due to cutting. To keep deformation of the structure within the permissible limits due to static loading, the structure should have adequate stiffness and proper structural configuration. Generally, there are two basic configurations used in machine tools.

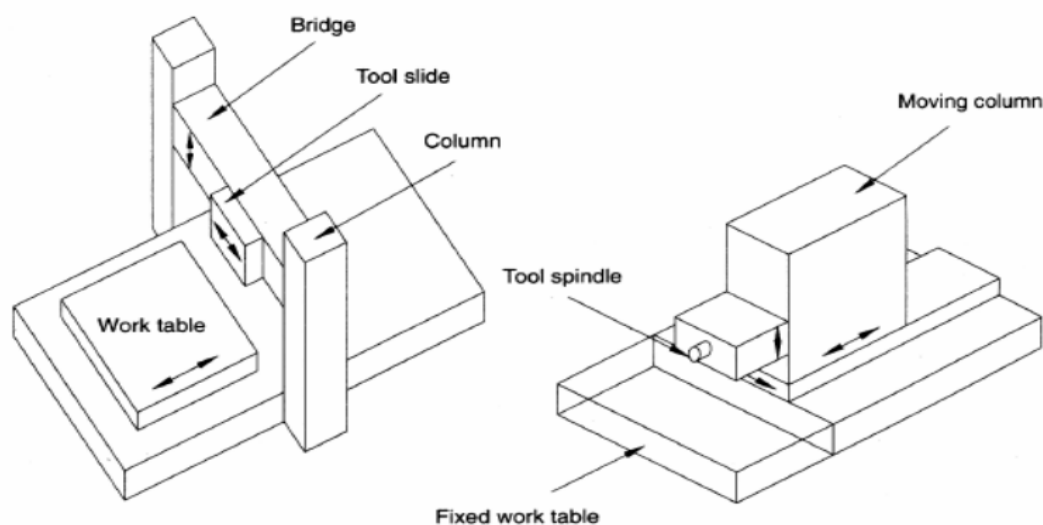


Figure VI.4: Commonly used configurations of machine tools.

IV.3.2 Dynamic Load

The Dynamic load is a term used for constantly changing forces acting on the structure when movement is taking place. These forces cause the whole machine system to vibrate.

The origin of such vibrations are:

- unbalanced rotating parts.
- Improper meshing of gears.
- Bearing irregularities.
- Interrupted cuts while machining (like in Milling)

The effect of these vibrations on the machine performance is reduced by:

- Reducing the mass of the structure.
- Increasing the stiffness of the structure.
- Improving damping properties.

IV.3.3 Thermal Load

In a machine tool, there are a number of local heat sources, which cause the thermal gradients within the machine. some of these sources are :

- Electric motor.
- Friction in mechanical drives and gearboxes.
- Friction bearings and guide ways.
- Machining process.
- Temperature of surrounding objects.

These heat sources cause localised deformation resulting in considerable inaccuracies in machine performance. Following steps are generally taken to reduce the thermal deformation:

- External mounting of drives i.e. motors and gearboxes.
- Dissipation of frictional heat from bearings and guide ways by proper lubrication system.
- Dissipation of heat generated from the machining process by proper coolant system and swarf removal system.
- Thermo-symmetric design of the structure.

IV.4 Guideways

Guide ways are mainly used in machine tools to

1. Control the direction or line of action of the carriage or the table on which a tool or a work is held.
2. To absorb all the static and dynamic forces. The shape and size of the work produced on a machine tool also depends on geometric and kinematic accuracies of the guide ways.

When the machining is taking place, the rate of transitional movement (feed rate) can be as low as 20 mm/min. during positioning. The feed rate can be as high as 30m/min. for fine machined surfaces and for accurate positioning, the movement must be smooth and continuous, and free from any jerky movements.

The following points should be considered while designing the guide ways.

- Rigidity.
- Damping capability.
- Geometric and kinematic accuracy.
- Velocity of the slide.
- Friction characteristics.
- Wear resistance.
- Provision for adjustment of play.
- Position in relation to work area.
- Protection against swarf and damage.

IV.4.1 Types of guideways

Guide ways are mainly two types as per their contacting characteristics.

4.1.1 *Friction Guide ways*

The relation between moving part (Guide) and stationary part (Guide way) contacting directly each other.

4.1.2 *Anti-Friction Linear Motion Guide ways*

Here the contact between guide and guide way may be separated by the third element i.e. Ball, Roller or hydraulic oil film in case of Hydro dynamic or hydrostatic guide way systems.

IV.4.2 Different Shape of Guide Ways

Most commonly used shape of building elements of slide ways are

1. V-Type
2. Flat type
3. Dove Tail Type
4. Circular or cylindrical type

The selection of the proper shape is based on the magnitude and direction of the load to be carried, position of transmission, wear characteristics and provisions for wear adjustments, ease of assembly and economy in fabrication, effective lubrication and the easy chip disposal.

All the four types of shapes have their own merits and demerits and thus sometimes it becomes desirable to use a combination of these slide ways on the machine tools.

4.2.1 *V-Type Guide Ways:*

Slide ways are advantageous because of the automatic adjustment by the gravity action which always keeps the surface in contact, thus the possibility of any play is eliminated. In addition, the wedging action due to cross winding is also prevented and there is no possibility of chips

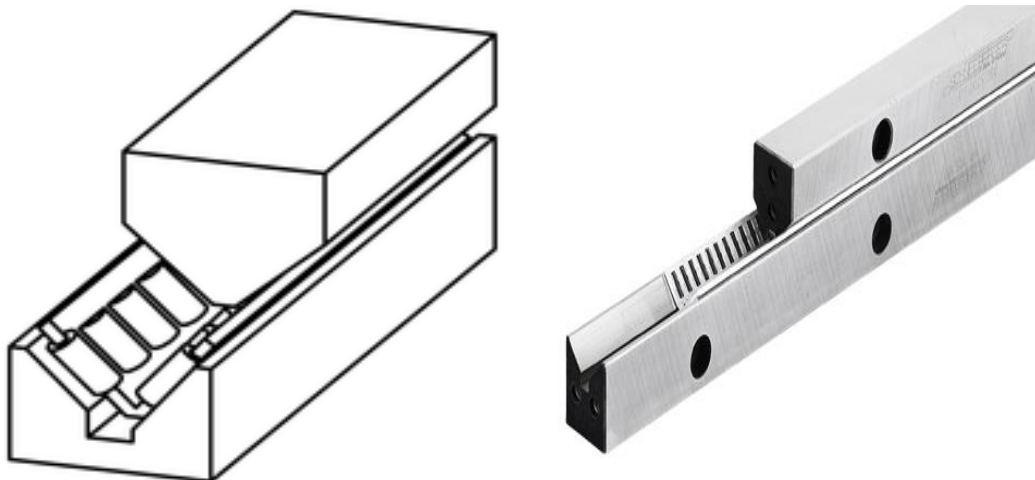


Figure VI.5: V-type guideways.

falling on the V-surface and getting entrapped into it. It has no tendency to accumulate dust. The Disadvantages of V-Type guides is that it wears away rapidly due to lack of bearing surface and is difficult to manufacture.

4.2.2 Flat Type Guide Ways

Slide ways are simple in construction and offer quite a large bearing area to the moving parts. Therefore to overcome the disadvantage of V-type slide ways by the advantages of the flat type slide ways. Separate guides are provided for the saddle and tail stock movements so that any wear caused by the saddle movement does not affect the height of tail stock centre.

The f Mt bed guides the saddle by the side guides and in order to prevent lifting movement the retaining pieces are fitted below the flat bed.



Figure VI.6: plat guideways.

4.2.3 Dove Tail Type Guideways

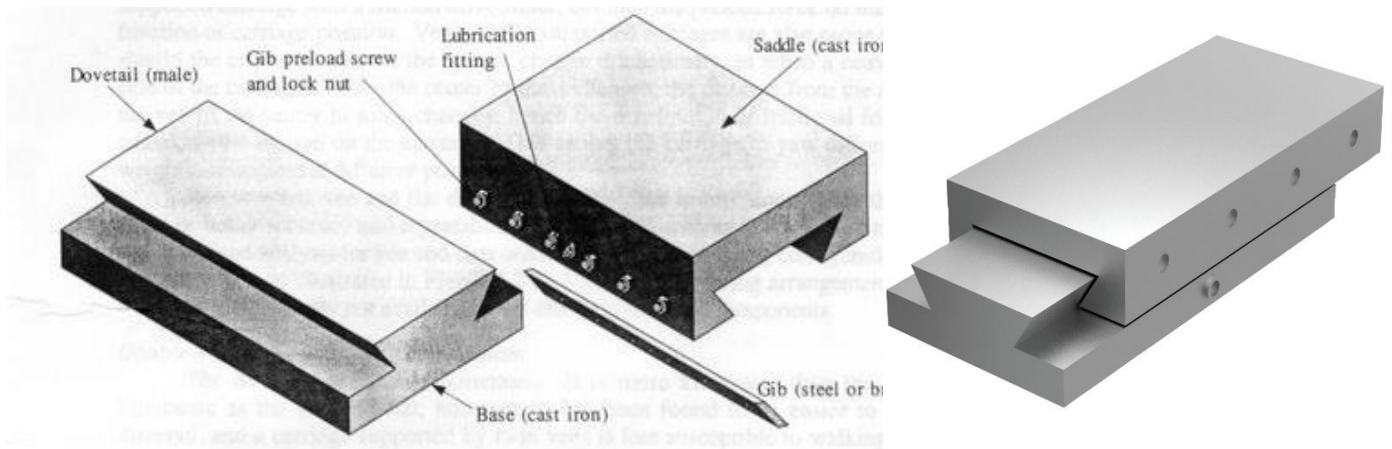


Figure VI.7: Dove Tail Type Guideways.

This type slide ways are preferred when location of the moving parts is considered essential. These are generally used for milling machine tables, saddles and knees. In dove tail type slide ways, adjustment for wear can be made by parallel blocics pushed by set screws. DOVE tel slide ways occupy small space. A Gib is provided. So that it can adjusted to ensure that the two element of the slide area good sliding fit.

4.2.4 Cylindrical Type Guideways

This slide fulfils the condition of kinematic principles being fully constrained. These guides are used in the pillar or radials drilling machines.

Clearance between mating surfaces of slide ways are inevitable because of wear and manufacturing imperfections. Clearance between flat ways may be controlled periodically by means of their gibes or strips.



Figure VI.8: Cylindrical Type Guideways.

Stick-slip motion of slide ways caused by frictional resistances between the sliding surfaces can be controlled by using anti-friction ways.

IV.4.3 Anti-friction

Different Types of Anti-Friction Guide-ways are

- a) Hydro-Static Guideways.
- b) Aerostatic Guideways.

4.3.1 *Hydro-static Guide ways:*

In hydrostatic guideways, air or oil is pumped into the small pockets or cavities machined into the carriage or slides which are in contact with the guide way. The pressure of fluid gradually reduces to atmospheric pressure as it sweeps out from the pockets, through the gap between slide and guide ways. The hydrostatic guide way provides almost a friction less condition for the movement of the slide. For the efficient operation, it is very important that the fluids and guide ways are kept clean and also the hydro-static guide ways need a very large surface area to provide adequate support.

4.3.2 *Aerostatic Guideways:*

In aerostatic guide ways, the slide is raised on a cushion of compressed air which entirely separates the slide and the guide way surface. The major limitation of this type of guide ways as a low stiffness which limits its use for positioning application only e.g. CMM and other measuring instrument. The selection of guide ways for a particular application basically depends upon the requirements of the load carrying capacity, damping property and the traverse speed. In order to get maximum benefit most of the machine tool manufacturers make use of a combination of anti-friction and friction guide ways with Turcite /PTFE lining. Such combination improves load carrying capacity through the use of anti-friction guide ways and damping property by using guide ways [11].

In aerostatic guide ways, the slide is raised on a cushion of compressed air which entirely separates the slide and the guide way surface. The major limitation of this type of guide ways as a low stiffness which limits its use for positioning application only e.g. CMM and other measuring instrument. The selection of guide ways for a particular application basically depends upon the requirements of the load carrying capacity, damping property and the traverse speed. In order to get maximum benefit most of the machine tool manufacturers make use of a combination of anti-friction and friction guide ways with Turcite/PTFE lining. Such combination improves load carrying capacity through the use of anti-friction guide ways and damping property by using guide ways [11].

IV.5 Ball bearing

Ball bearings are used primarily to support rotating shafts in mechanical equipment. They can be found in everything from personal computers to passenger cars. They are of simple design and can be precision made in mass production quantities. They can support heavy loads over a wide speed range and do it virtually friction free. They come in many different sizes and shapes, are relatively inexpensive, and require little or no maintenance. They have predictable design lives and operating characteristics and are truly a valuable asset to the rotating equipment industry of today.

IV.5.1 Description

All ball bearings has an inner ring (IR), and an outer ring (OR), a group of balls are followed and a separator to contain them is in middle of the OR and the IR. The outer diameter of the inner ring (IROD) and the inner diameter of the outer ring (ORID) have a groove in which the balls roll on. This groove is commonly called the pathway. The path way has a raised sides called the shoulders. The balls are held equally spaced around the annulus of the bearing by the separator. The basic dimensions of the bearing are the bore (B), outside diameter (OD), and the width (W) [10].

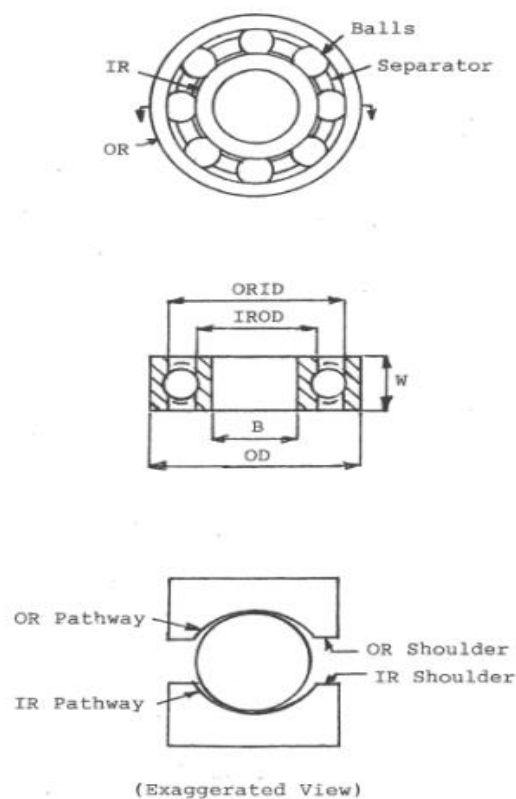


Figure VI.9: Ball bearing schematics [10].

IV.6 Bushing bearing

IV.6.1 Standard Linear Bushing

- Allowed Max. 10130N the basic dynamic load rating
- Shaft diameter from 5mm to 80mm
- Provide low friction on high-speed movement

- Can be selected resin retainer (standard), and steel retainer (for high temperature & vacuum)
- Corrosion resisting: the nickel-plated, Rayden treatment of Outer- sleeves, stainless steel ball.

IV.6.2 Aluminium Case Unit bushing bearing



Figure VI.10: bushing bearing.

- Integration of aluminum housing and linear bushing.
- Aluminum housing with a high hardness and lightweight.
- Combined with support rail.

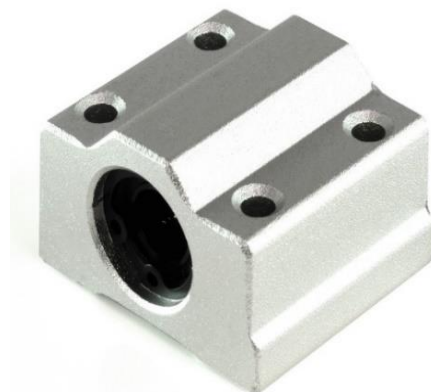


Figure VI.11: aluminum case bushing bearing.

IV.7 Lead screw

A lead screw turns rotary motion into linear motion combining a screw and a nut where the screw thread is in direct contact with the nut thread. In the case of roller screws, the rollers rather than the nut are in direct contact with the screw thread offering greater efficiency.



Figure VI.12: stainless steel trapezoidal lead screw.

IV.7.1 Types of lead screws

- Trapezoidal thread.
- Sharp thread.
- Buttress thread.
- Knuckle thread.
- Course thread.
- Diamond thread.
- Threaded nuts.
- Lead screw repair & reverse engineering.

IV.8 Timing belt

The classical timing belt consists of four components.

Cable Tension Member: A continuous helically wound glass fibre cable is the load-carrying element at the heart of the belt. This tension member provides the belt with enormous tensile strength with a high level of flexibility.

Polychloroprene Backing: A thin, strong, wear resistant polychloroprene rubber sleeve is bonded to the tension cable to provide a flexible protection.

Polychloroprene Teeth: Moulded integral with the polychloroprene backing, made of moderately hard, shear resistant rubber compound, the teeth are accurately formed and precisely spaced pulley engagement.

Nylon Facing: A tough, wear resistant nylon duck, with low coefficient of friction, protects the wearing surface of the teeth in the same manner as case hardening protects the surface of steel.

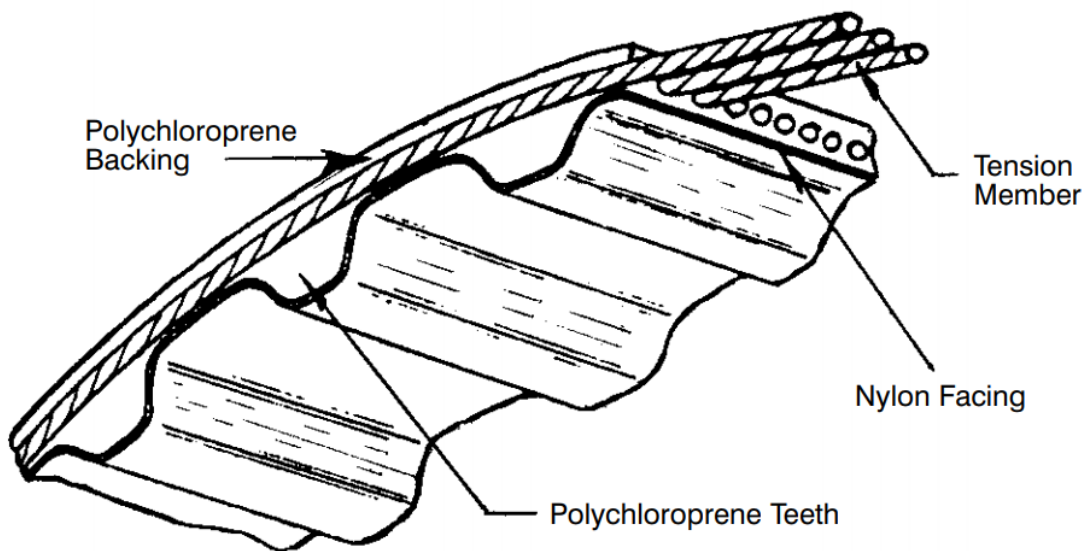


Figure VI.13: Timing Belt Construction.

We used in our CNC machine GT-2 type timing-belt that has the characteristics of the 20 teeth 5mm/8mm bore Aluminium timing pulley.



Figure VI.14: GT-2 Timing Belt.

IV.9 Application Part

IV.9.1 Design

In the process of designing the machine, we considered to build a multiple tasks machine, so we combined 3 machines in one, 3D printer, milling CNC machine & laser engraver, all in one design.

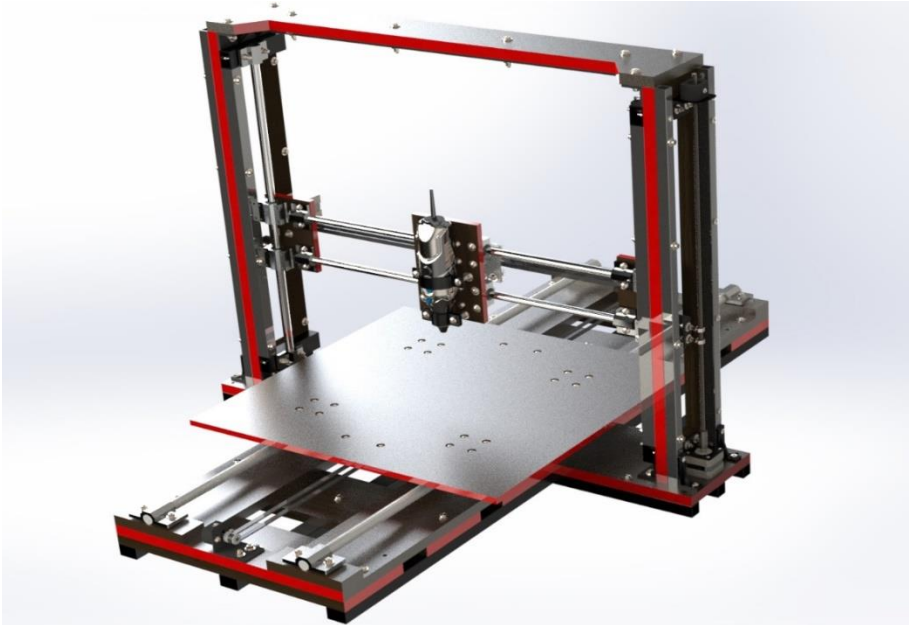


Figure VI.15: Our CNC machine design with SolidWorks.

9.1.1 Working space

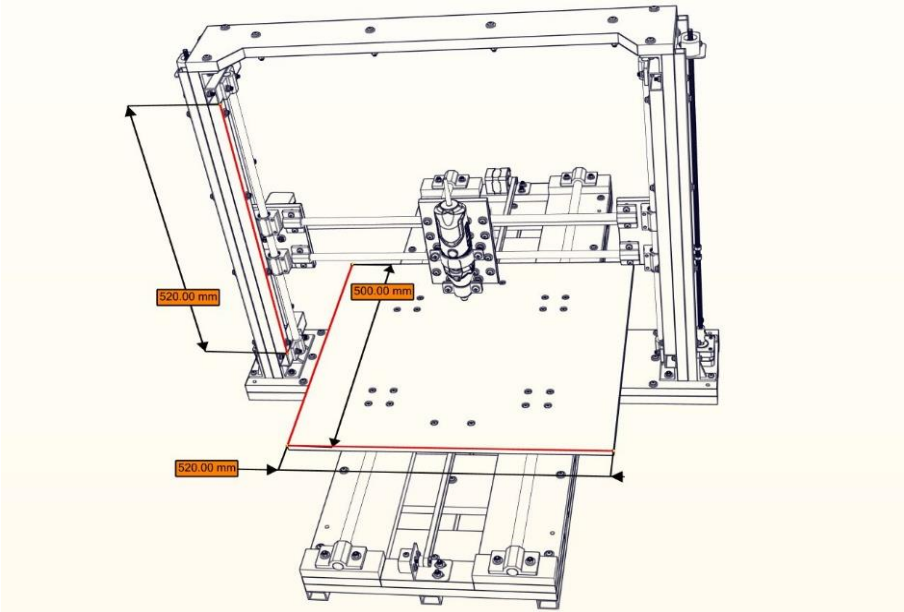


Figure VI.16: the volume of the maximum job work.

The working space of the machine is 500 x 520 x 520 mm

9.1.2 Size of the machine

X = 1084.00 mm

Y = 820.00 mm

Z = 699.23 mm

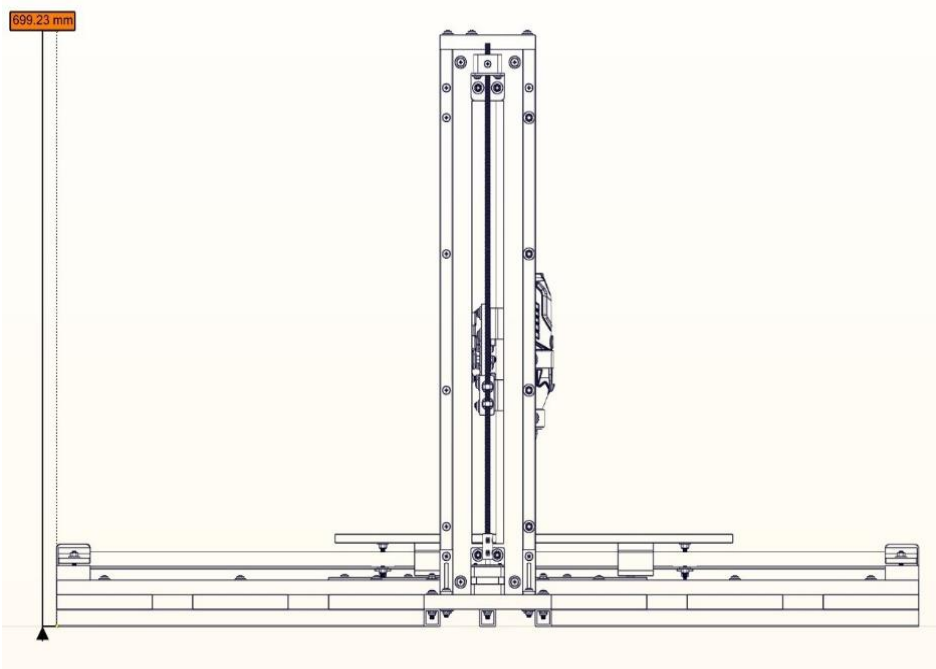
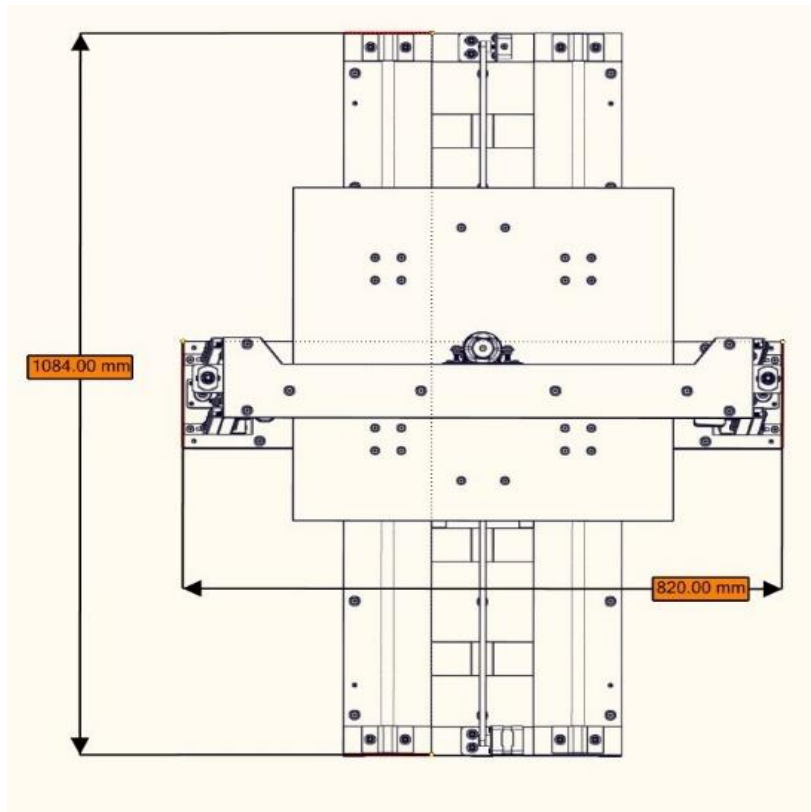


Figure VI.17: The full size of the machine.

IV.9.2 Machine parts

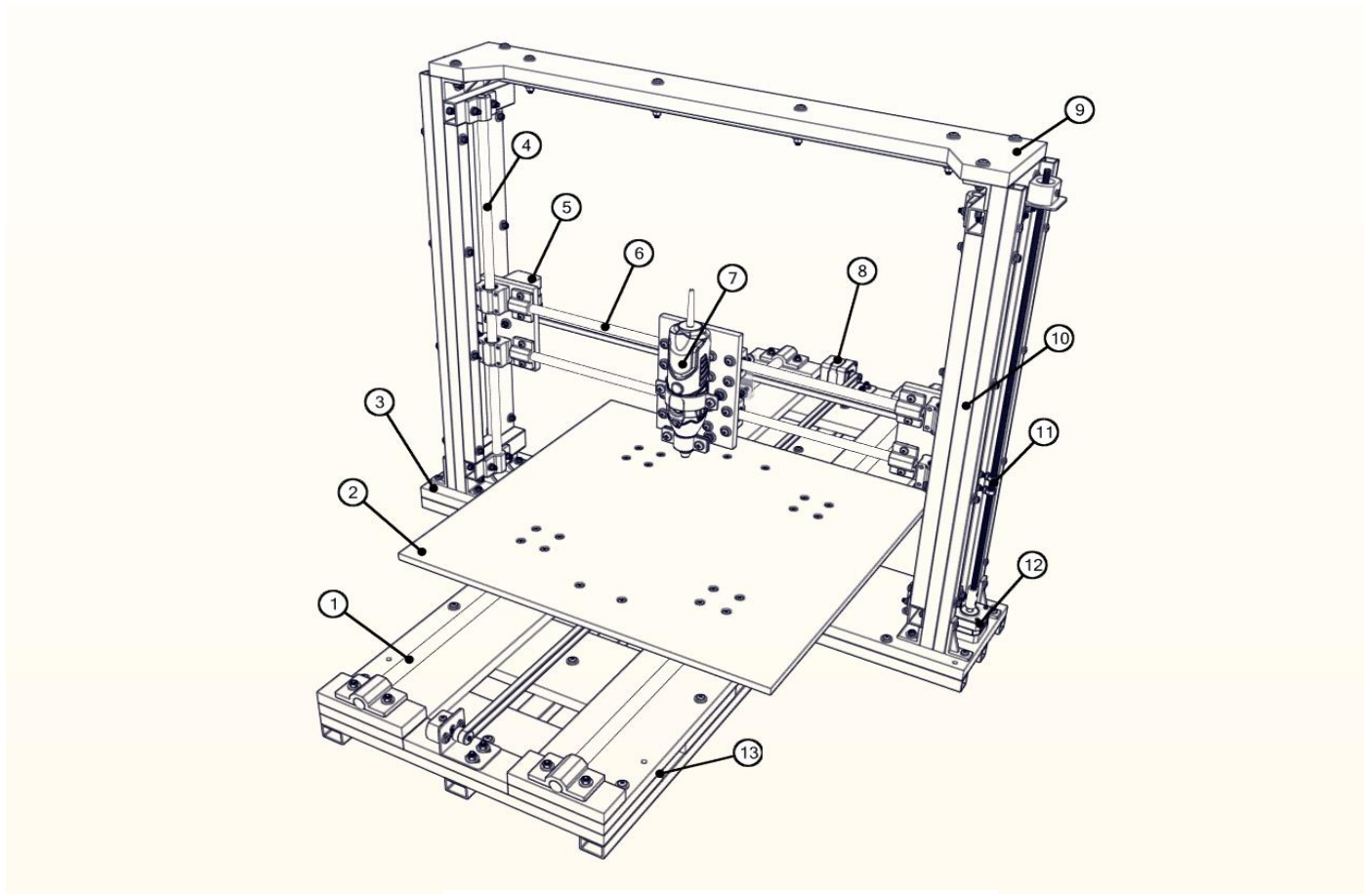


Figure VI.18: Our CNC Machine Parts.

3. X axis linear guideway stainless steel rod
4. Working plate
5. Y & Z axis body frame
6. Z axis linear guideway stainless steel rod
7. Y axis stepper motor
8. Y axis linear guideway stainless steel rod
9. Carving router motor
10. X axis stepper motor
11. The Frame
12. Rectangular stainless steel hollow rod for support
13. Z axis lead screw
14. Z axis stepper motor
15. X axis body frame

IV.9.3 Static study

In this study, we want to find the maximum resistance for our design structure to choose the right materials and edit what it needs to be improved in the design if necessary.

9.3.1 Calculation for motor performance

The torque required to lift or lower a load can be calculated by "unwrapping" one revolution of a thread. This is most easily described for a square or buttress thread as the thread angle is 0 and has no bearing on the calculations.

$$T_{raise} = \frac{Fd_m}{2} \left(\frac{l + \pi\mu d_m}{\pi d_m - \mu l} \right) = \frac{Fd_m}{2} \tan(\phi + \lambda) \quad \text{(VI. 2) [12] [13]}$$

$$T_{lower} = \frac{Fd_m}{2} \left(\frac{\pi\mu d_m - l}{\pi d_m + \mu l} \right) = \frac{Fd_m}{2} \tan(\phi - \lambda) \quad \text{(VI. 3) [12] [13]}$$

Where:

- T = torque (N.m)
- F = load on the screw (N)
- d_m = mean diameter (m)
- μ = coefficient of friction (common values are found in the adjacent table)
- l = lead (m)
- ϕ = angle of friction (rad)
- λ = lead angle (rad)

Screw material	Nut material			
	Steel	Bronze	Brass	Cast iron
Steel, dry	0.15–0.25	0.15–0.23	0.15–0.19	0.15–0.25
Steel, machine oil	0.11–0.17	0.10–0.16	0.10–0.15	0.11–0.17
Bronze	0.08–0.12	0.04–0.06	-	0.06–0.09

Table VI.2: Coefficient of friction for leadscrew threads [12].

The maximum torque for both Z-axis is 52 N.cm, from the equation (VI.2) we got:

Maximum force of 619 N equivalent to 63.16 kgf.

Thread	Major Diameter	Pitch	Pitch Diameter	Minor Diameter Male Thread	Minor Diameter Female Thread
M3.5	3.5	0.60	3.110	2.764	2.850
M4	4.0	0.70	3.545	3.141	3.242
M4.5	4.5	0.75	4.013	3.580	3.688
M5	5.0	0.80	4.480	4.019	4.134
M6	6.0	1.00	5.350	4.773	4.917
M7	7.0	1.00	6.350	5.773	5.917
M8	8.0	1.25	7.188	6.466	6.647
M9	9.0	1.25	8.188	7.466	7.647
M10	10.0	1.50	9.026	8.160	8.376
M11	11.0	1.50	10.026	9.160	9.376

Table VI.3: ISO threads specification [14].

The maximum force obtained from the motor is:

$$M_m = 0.40 \text{ N.m}$$

$$M_m = 40 \text{ N.cm}$$

$$M = F \cdot D/2 \quad \longrightarrow \quad F = 2M / D$$

$$F = 2 \times 40 / 1,2 = 80 / 1,2 = 66,66 \text{ N}$$

The complex shapes and variation of materials and forces made the use of finite elements the perfect solution to this problem.

Therefore, we applied this method in SolidWorks program.

9.3.2 SolidWorks software

CAD software SolidWorks is a 3D parametric mechanical design application that allows designers to quickly sketch their ideas, experiment with features and dimensions to produce accurate models and drawings.

Concepts

Parts are the building blocks of SolidWorks software. Assemblies contain parts or other assemblies, called subassemblies.

A SolidWorks model consists of 3D geometry that defines its edges, faces, and surfaces. SolidWorks software allows you to quickly build precise models. His models are:

- Based on 3D modeling
- Component-based

3D modeling

SolidWorks adopts the 3D modeling approach. When you design a part, you create a 3D model, from the initial sketch to the final result. From this model, you can create 2D drawings or constrain parts or subassemblies to create 3D assemblies. You can also create 2D drawings of 3D assemblies. A model designed using SolidWorks can be visualized in its three dimensions, that is to say in its final appearance after manufacture.

9.3.3 Finite Element Analysis (FEA) or Finite Element Method (FEM)

- The Finite Element Analysis (FEA) is a numerical method for solving problems of engineering and mathematical physics.
- Useful for problems with complicated geometries, loadings, and material properties where analytical solutions cannot be obtained.

1. Common FEA applications

- Mechanical
- Aerospace
- Civil
- Automotive Engineering
- Structural / Stress Analysis: Static/ Dynamic _ Linear / Nonlinear
- Fluid Flow
- Heat Transfer
- Electromagnetic Fields
- Soil Mechanics
- Acoustics
- Biomechanics

2. Advantages

- Irregular Boundaries
- General Loads
- Different Materials
- Boundary Conditions

- Variable Element Size
- Easy Modification
- Dynamics
- Nonlinear Problems (Geometric or Material)

3. Principals of FEA or FEM

The finite element method (FEM), or finite element analysis (FEA), is a computational technique used to obtain approximate solutions of boundary value problems in engineering.

Boundary value problems are also called field problems.

The field is the domain of interest and most often represents a physical structure.

The field variables are the dependent variables of interest governed by the differential equation.

The boundary conditions are the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field.

9.3.4 *Y axis study for Stress and for displacement*

First, we are going to run a simulation study of our Y-axis assembly involving small displacement contact, we are going to run an analysis using SolidWorks detection interferences tool to find out if we have any interference in our assembly.

Then we build a static simulation study, first we choose the materials used by their properties for each part of the assembly.

After that, we used fixed geometry restraint in the middle of our fixed bushing bearings.

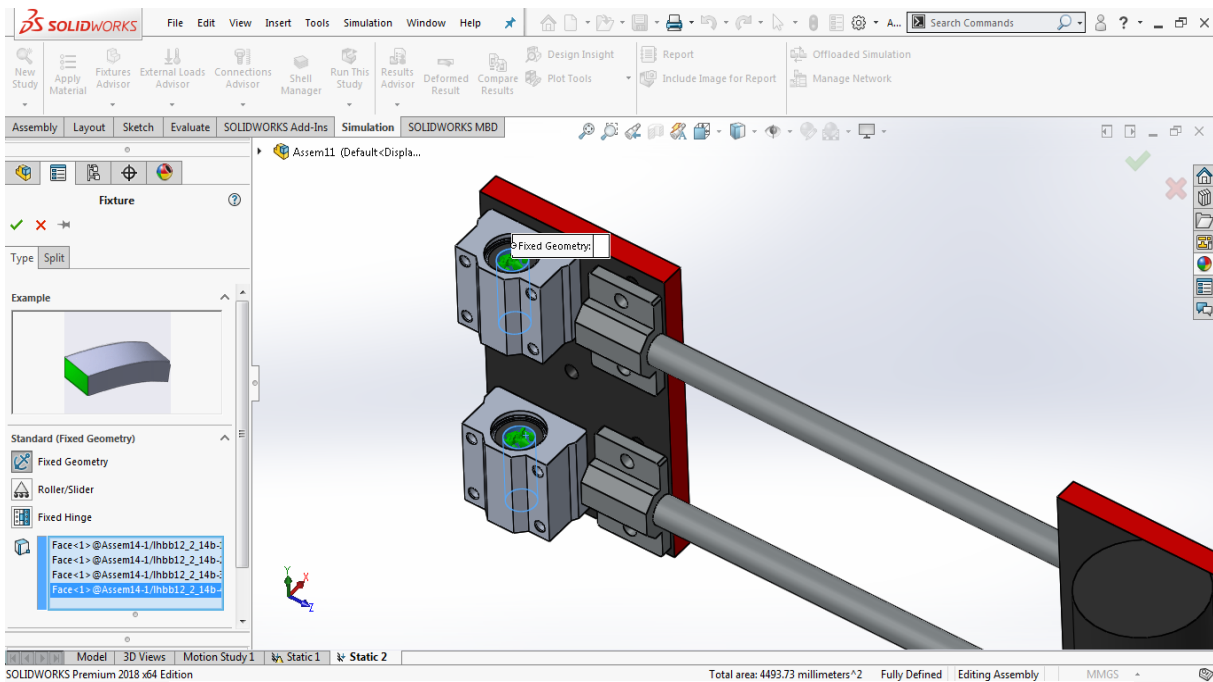


Figure VI.19: Fixed geometry restraint inside of the bushing bearing.

In addition, we apply a couple of external loads of 100N on the head of the router in x-axis direction where the forces are most significantly high.

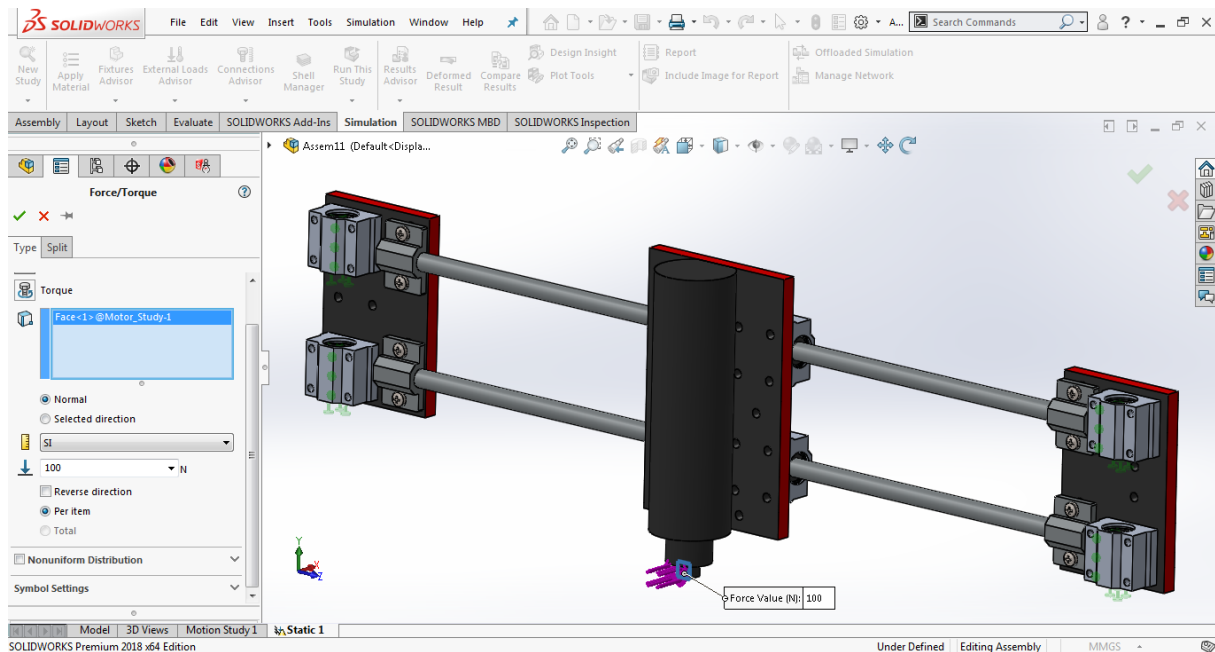


Figure VI.20: Applying external load at the router head.

Chapter IV Mechanical Study

Next, we create a mesh model; we adjust the maximum mesh size by 10mm, and the minimum by 2mm according to the size of our assembly and processing time and accuracy, then we start the mesh process.

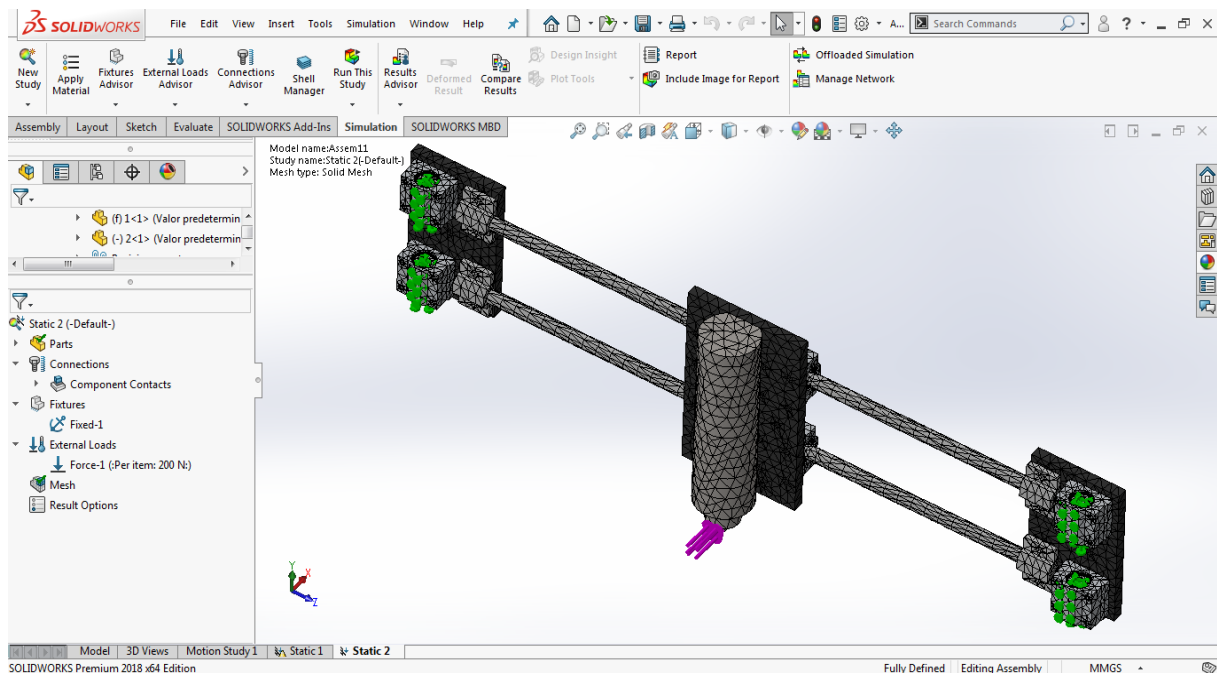


Figure VI.21: Creating the mesh model.

The maximum stress is **92.35 Mpa** located at the stainless steel rods and lower than the maximum value of the material that is fixed at **413.613 Mpa**.

The result is shown below in this simulation:

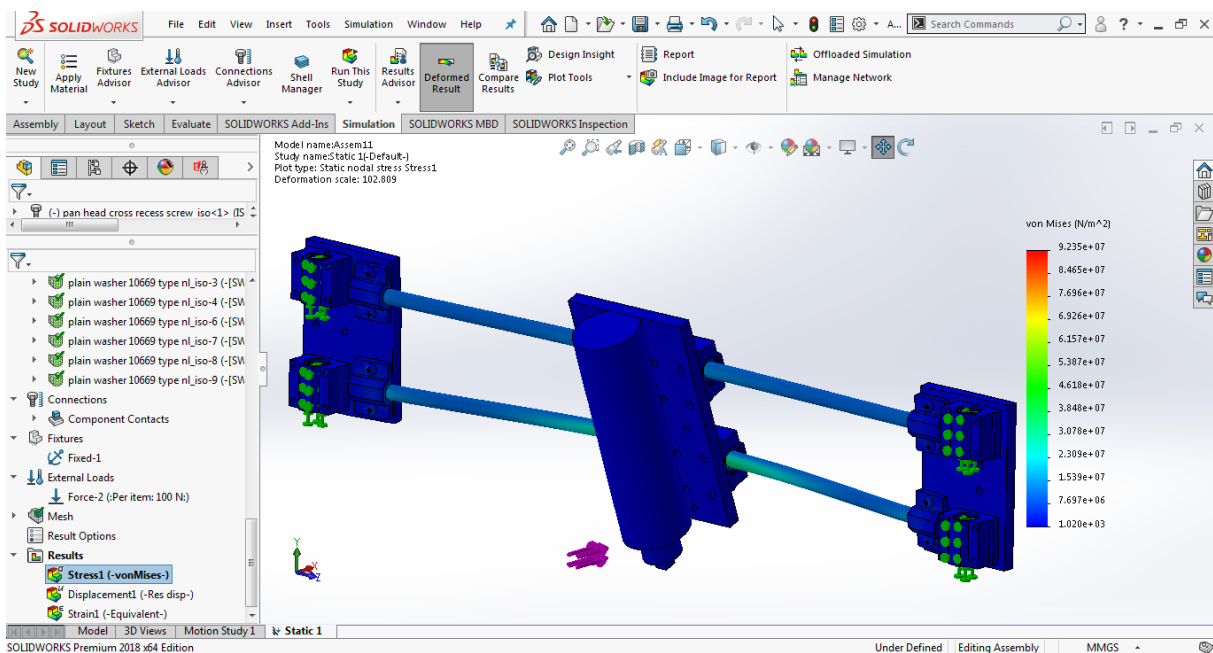


Figure VI.22: The stress simulation at the at the stainless steel rods.

- The maximum displacement value is **0.7048 mm**.

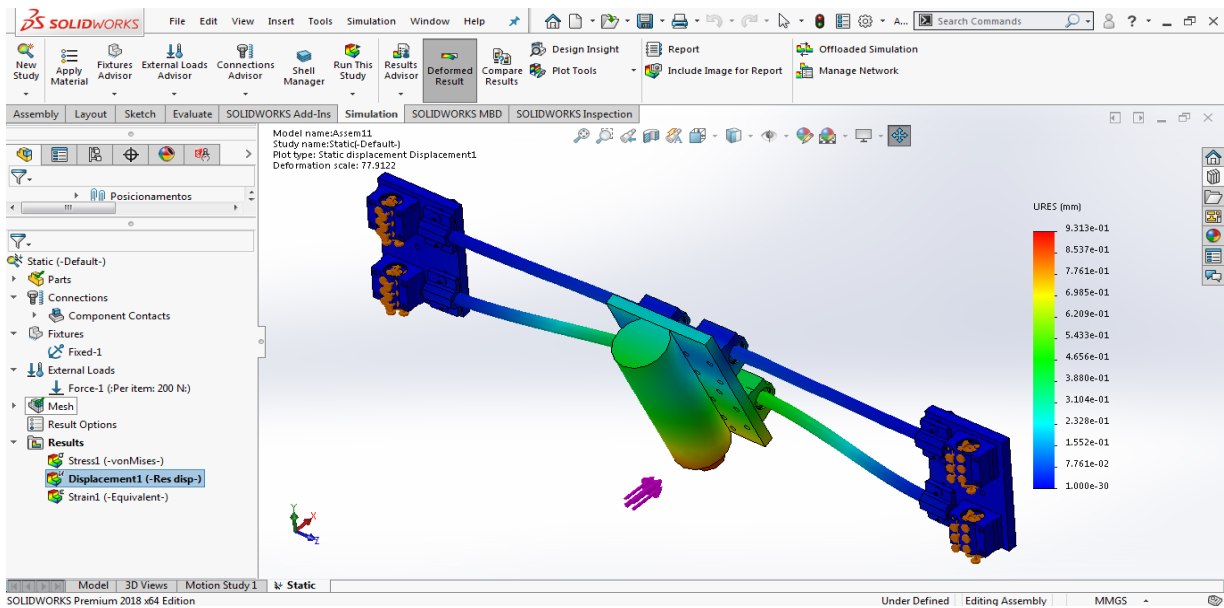


Figure VI.23: The displacement simulation of the router head after the update.

From the result obtained, we see that the displacement is significantly high compared to a precise CNC machine, so we are going to update the **MDF** material to **aluminium alloy 1060**, it is going to improve the resistance by 31.41%.

- The maximum displacement value is **0.4834 mm**.

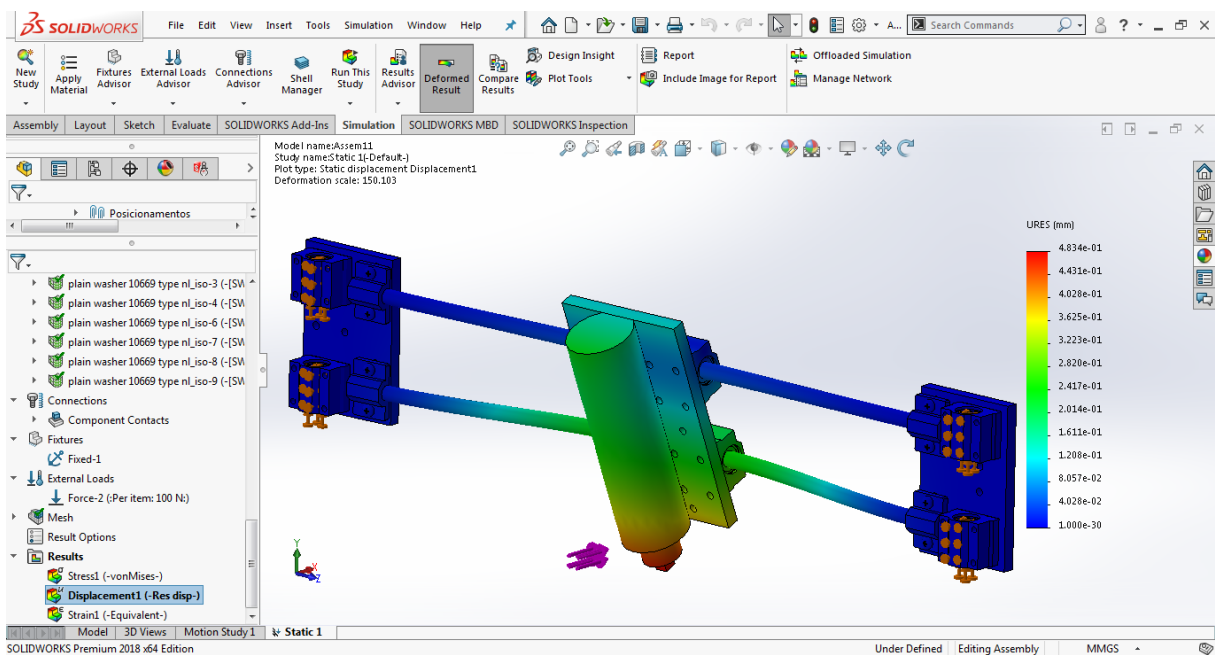


Figure VI.24: The displacement simulation of the router head.

9.3.5 X axis study for Stress and for displacement

The same process was done with the X-axis compared with Y-axis and the result we got is shown below:

- The maximum displacement that could happened at 200N is **0.568 mm**.
- The minimum displacement that could happened at 200N is **10^{-30} mm**.

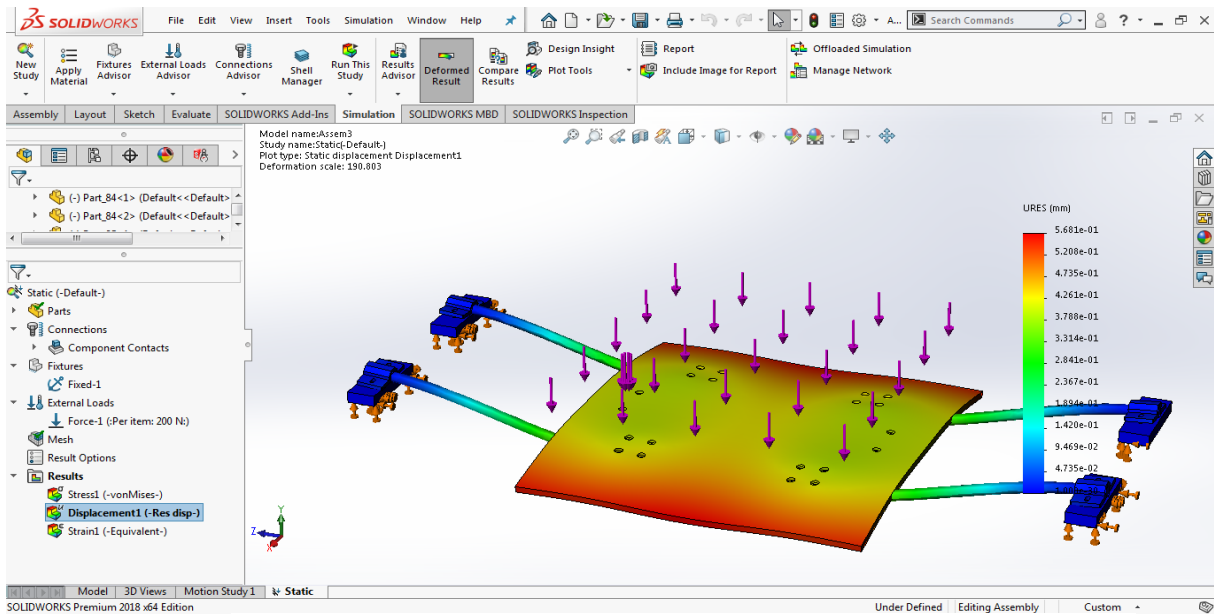


Figure VI.25: The displacement simulation of the table.

The maximum stress is **26.5 Mpa** located at the stainless steel rods with a diameter of 16mm and lower than the maximum value of the material that is fixed at **413.613 Mpa**.

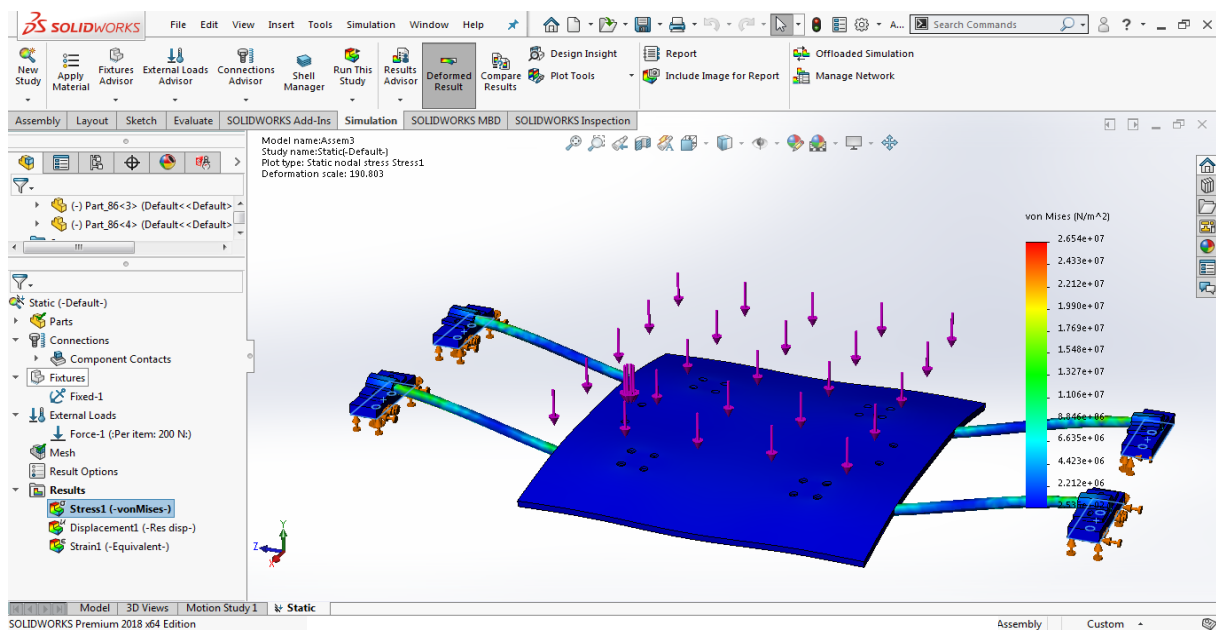


Figure VI.26: The stress simulation of the table.

IV.9.4 Used materials

The used materials and their properties:

Name	Yield strength	Tensile strength	Elastic modulus	Poisson's ratio	Mass density	Shear modulus
MDF		1.8e+07 N/m ²	4e+09 N/m ²	0.25 N/A	750 kg/m ³	2.5e+09 N/m ²
Chrome stainless steel	1.72339e+08 N/m ²	4.13613e+08 N/m ²	2e+11 N/m ²	0.28 N/A	7800 kg/m ³	7.7e+10 N/m ²
1023 Carbon steel	282.685049 N/mm ²	425 N/mm ²	205 Mpa	0.29 N/A	7858 kg/m ³	

Table VI.4: building material properties [15] .

In this machine, we used wood as structure supported by metal rods, and metal pieces as a fundamental guideways parts.

9.4.1 Type of wood

We used MDF wood parts all over the CNC machine, for its strong resistance and resilience to the outside effects that may be caused during the workflow.

MDF boards (**Medium Density Fiberboard**)

Fibreboard consists of wood fibers or other lignocellulosic materials with a thickness of 1.5 mm, with application of heat and / or pressure.

The cohesion comes from:

- Felting of these fibers and their intrinsic adhesive properties (wet process), in the case of soft, semi-hard and hard fiberboard;
- The addition to the fibers of a synthetic binder (phenol-formaldehyde glue) (process dry), case of MDF panels (density 600 kg / m³).

Other additives could be added.

9.4.2 Type of metal rods

Chrome stainless steel metal rods.

9.4.3 Type of support metal

Carbon steel 1023 rectangular hollow metal rods.

IV.10 The final result

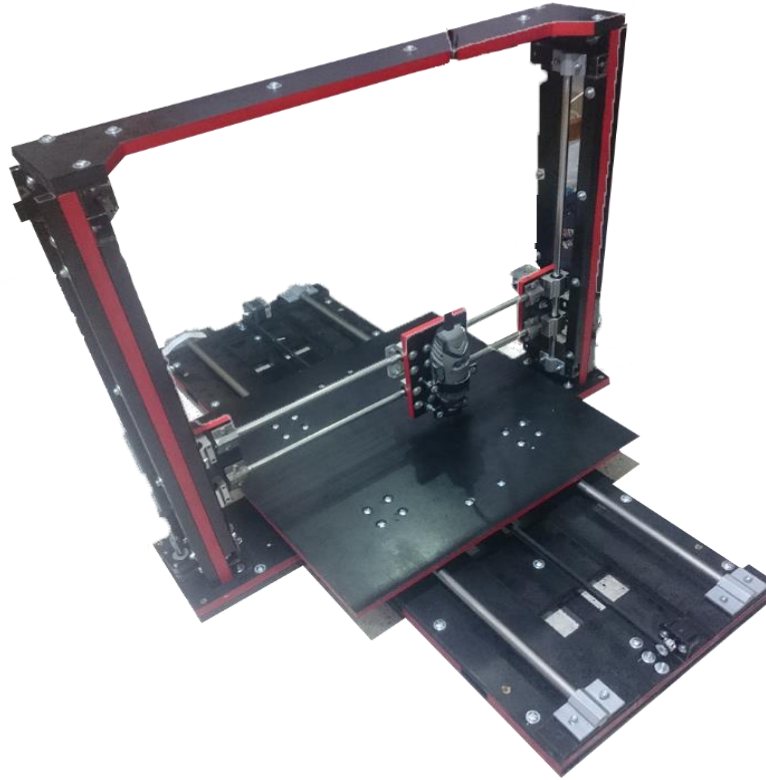


Figure VI.27: The final building process.

IV.11 Conclusion

The finite element method requires a high computational complexity to design and choose the right materials for our machine. CAD software like SolidWorks is very important to breakdown the required complexity.

After studying the structure of the machine, we proved that using timing belts is possible in milling process at low feed rate, not the same if we use it as 3D printer that operates in high speed.

General conclusion

Currently there is a lot of troubleshooting in CNC machines that causes problems to the manufacturing process, due to improper settings or tools with bad maintenance. That's why we tried in this master's dissertation, to find the proper solutions to reduce or to stop those issues using Artificial Intelligence with Neural Network. After doing some researches and experiments, we designed and built our CNC machine and Neural Network library. The objective is after learning step by step using enough data, is to learn when CNC Machine stop or reduce the speed when it is necessary.

Finding the proper parameter in first time for milling different materials in CNC machines, could consume time and money, or cause many other risks. In fact, there are a lot of variables that can affect the milling process such the power of motors and spindle, the property of materials, the tools used, the feed rate and the cutting depth and even the structure of the machine itself. However, with Artificial Intelligence tuning these parameters could be done automatically.

Most of errors happened when we operate the CNC machine at relatively high speed. Because the torque of stepper Motors decreased due to the back Emf phenomenon, at very low speed the change in current is no more detectable, while operating the machine the heat generated by the stepper motors can change its characteristic temporally. Therefore, it affects the current reading. This issue is solved by using Neural Network algorithm which learn to recognize the non-desired current variations. After collecting the needed data, and training step, we could detect when the motors are having trouble, and make the good decision such as decrease the speed or stop the machine automatically. This method can be applied to many kinds of machines operating with stepper motors such 3D printer, plasma cutter, robotic arms...

For future works, we can suggest an automatic collecting data process, by designing a system that can apply different external forces to stepper motors while running at different speeds and accelerations, in order to simulate all the possible scenarios. Also, it is better to use a leading screw mechanism instead of the timing belt to increase the torque and the speed of stepper motors. This suggestion turns out more efficient.

Annex

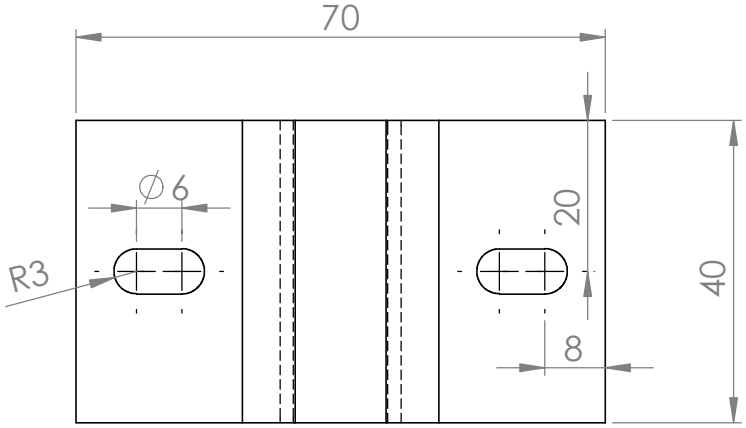
In the following annex we are going to show the drawing part.

4 3 2 1

x4

F

F

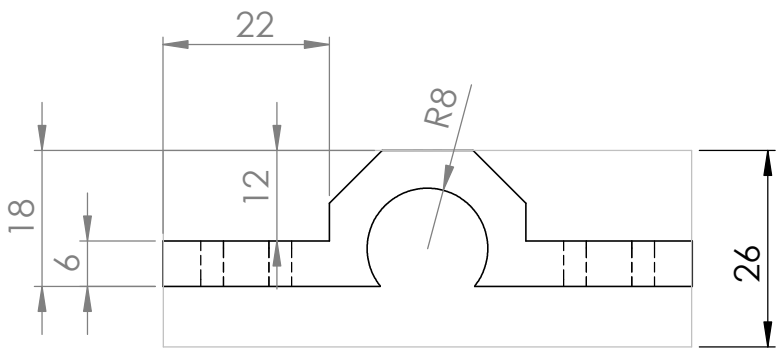


E

E

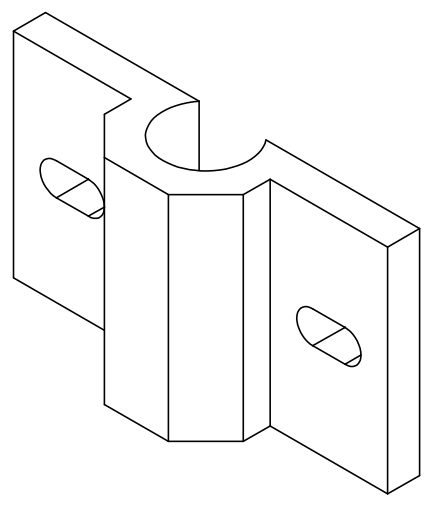
D

D



C

C



B

B

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

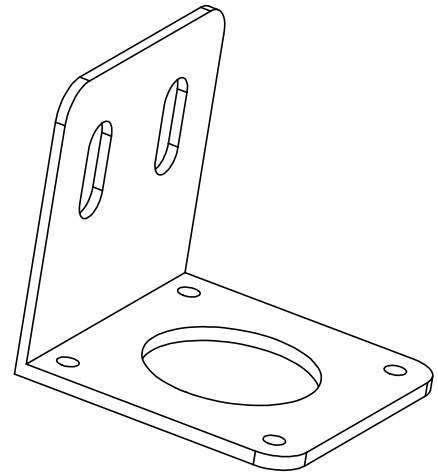
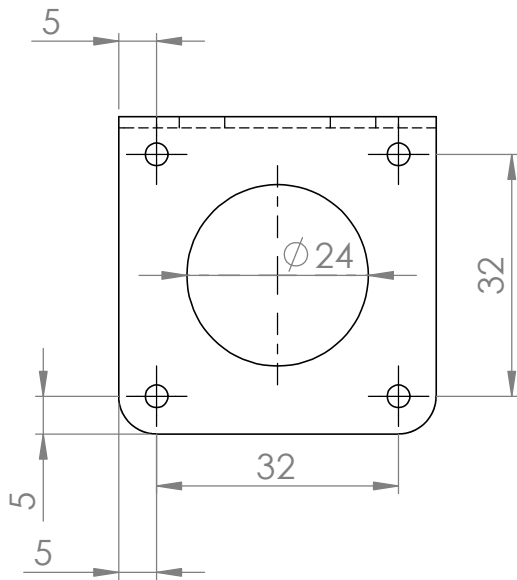
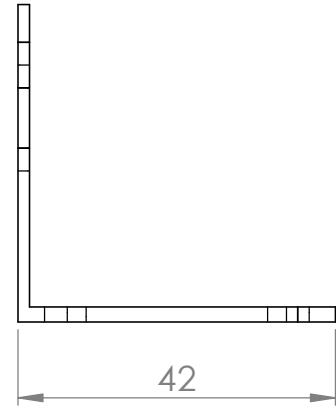
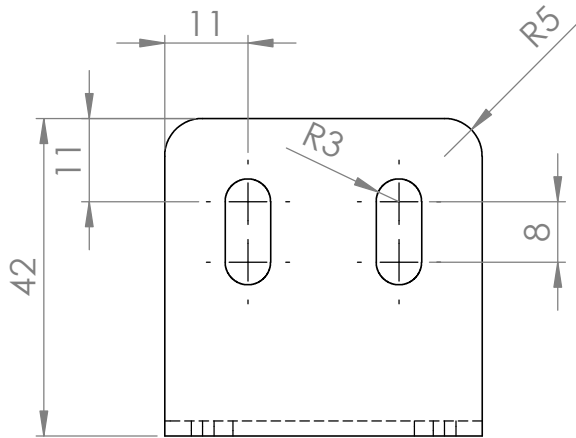
TITLE:	
MATERIAL:	1023 Carbon steel
DWG NO.	Rod Holder
WEIGHT:	
SCALE: 1:1	SHEET 1 OF 1

A

A

4 3 2 1

A4



x1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

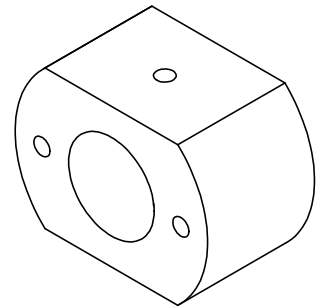
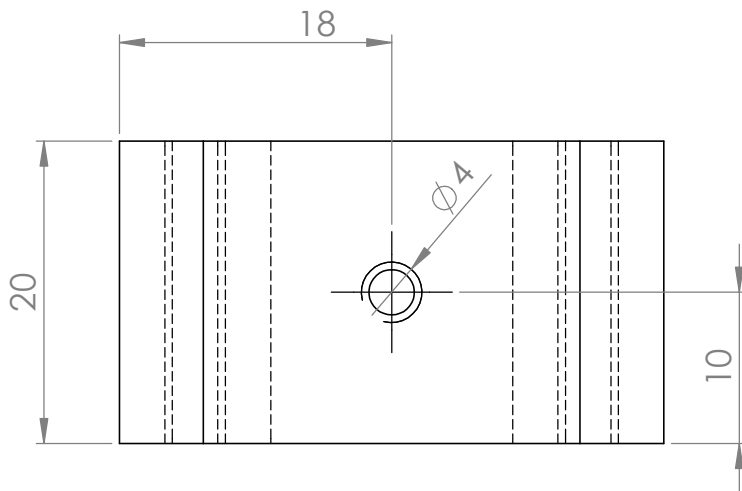
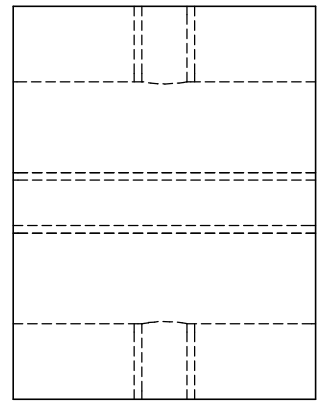
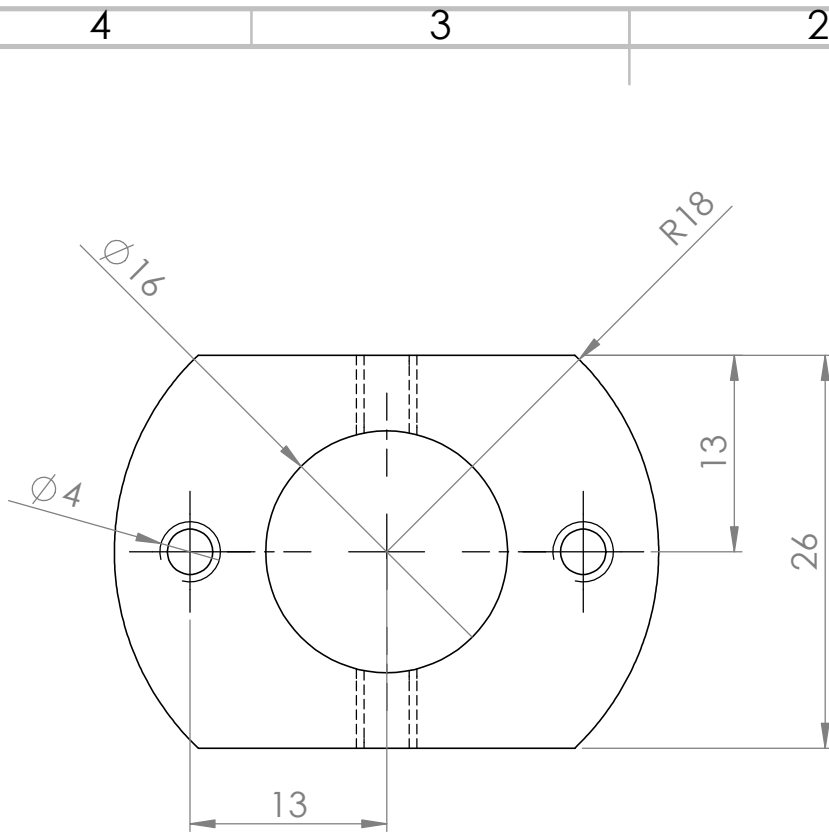
DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:	
MATERIAL:	Steel
DWG NO.	Motor Holder
WEIGHT:	
SCALE: 1:1	SHEET 1 OF 1

A4



x1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:

MATERIAL:

Steel

DWG NO.

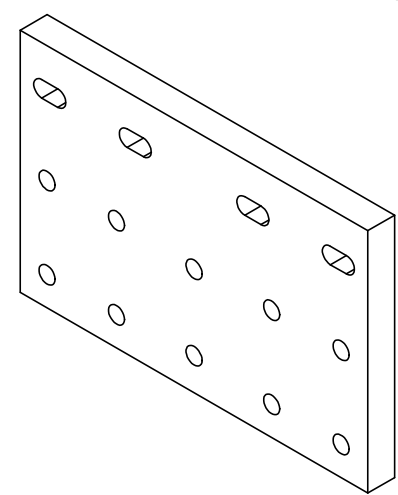
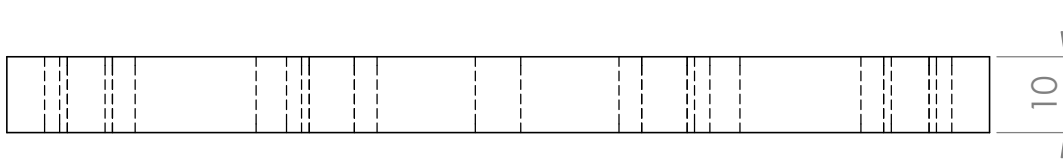
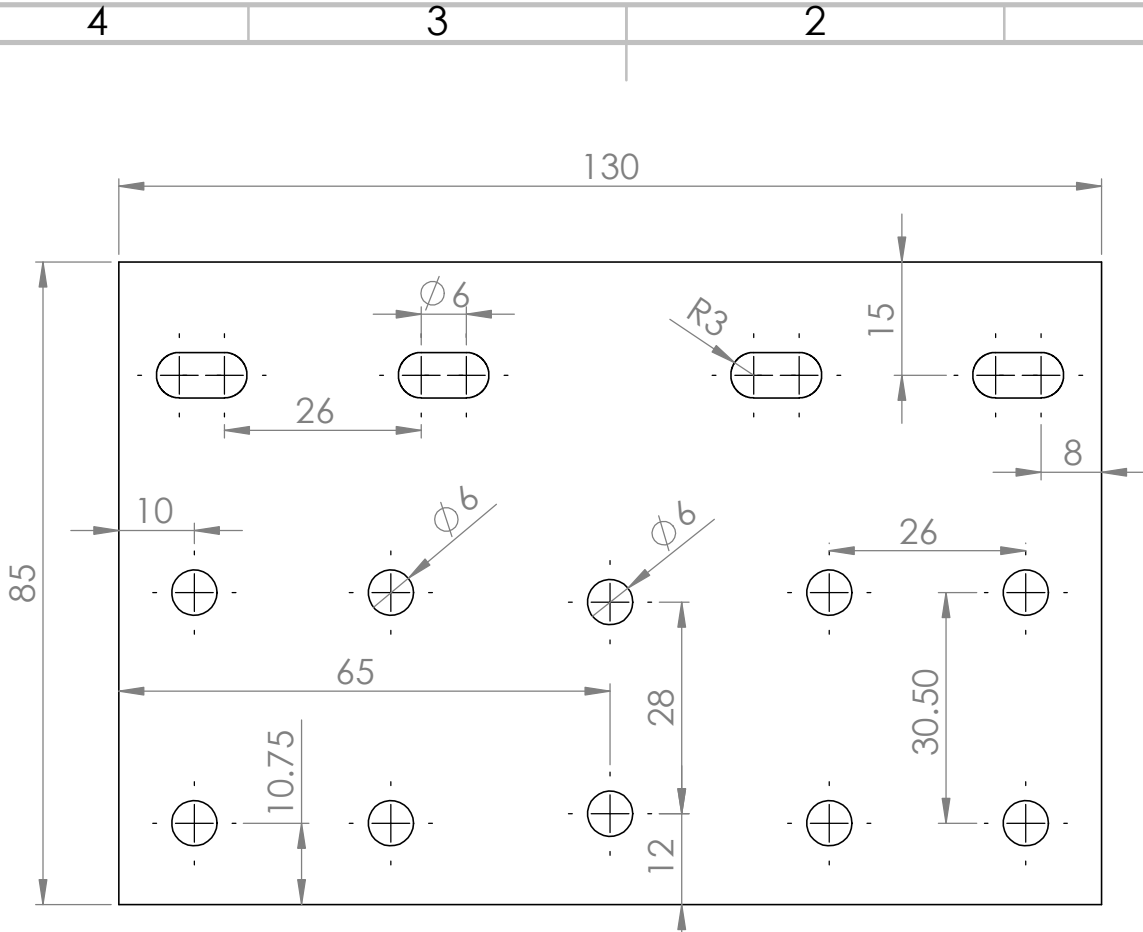
Ball bearing Holder

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 SURFACE FINISH:
 TOLERANCES:
 LINEAR:
 ANGULAR:

FINISH:

DEBURR AND
 BREAK SHARP
 EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:		DWG NO.	
Part_75		A4	
		SHEET 1 OF 1	

MATERIAL:
 Wood (MDF)

WEIGHT:

SCALE: 1:1

A

A

4

3

2

1

F

F

E

E

D

D

C

C

B

B

References

- [1] Fu HJ, DeVor RE, Kapoor SI. A mechanistic model for the prediction of the force system in face milling operations.
- [2] Berry M., Linoff G.: "Data Mining Techniques for Marketing, Sales and Customer Support", Wiley Publishing, 1997.
- [3] Doudge N.: "The Brain That Changes Itself: Stories of Personal Triumph from the Frontiers of Brain Science", Penguin Books, 2007.
- [4] Schwartz J.M., Begley S.: "The Mind and The Brain", Harper Perennial, 2003.
- [5] Chester D.L.: "Why Two Hidden Layers are Better than One", IJCNN-90-WASH-DC, Lawrence Erlbaum, vol. 1, pp. 265-268, 1990.
- [6] Lawrence S., Giles C.L., Tsoi A.C.: "Lessons in Neural Network Training: Overfitting May be Harder than Expected", Proceedings of the Fourteenth National Conference on Artificial Intelligence, AAAI-97, AAAI Press, Menlo Park, California, pp. 540-545, 1997.
- [7] "Implementing the model-view-viewmodel" pattern, [Online]. Available: <https://msdn.microsoft.com/en-us/library/ff798384.aspx>.
- [8] Paul Acarnley: "stepper motors a guide to theory and practice 4th edition", the institution of engineering and technology. IET control engineering series 63 . series edition : Professor D.P Atherton.
- [9] John Nussey: 'Arduino for dummies', Published by John Wiley & Sons, Ltd, 2013.
- [10] Robert P. Tata, P.E.: "Ball Bearing Design and Applications", 2011.
- [11] Y T Li and H Ding School of Mechanical Engineering, Robotics Institute, Shanghai Jiao Tong University, Shanghai, Design analysis and experimental study of aerostatic linear guideways used in a high acceleration and high precision xy stage, 2006.
- [12] Machine design. I. Nisbett, J. Keith. II. Shigley, Joseph Edward. Mechanical engineering design. III. Title. TJ230.S5 2014.
- [13] V.B Bhandari design of machine elements, third edition.
- [14] According to ISO965.
- [15] SolidWorks Software.
- [16] Simon Haykin McMaster, 'Neural Networks and Learning Machines Third Edition' University Hamilton, Ontario, Canada, 1999.
- [17] Griffiths, David Jeffery. Introduction to Electrodynamics (3rd ed). (2012).
- [18] Self-Inductance, Naval Electrical Engineering Training Series, Module 02: Introduction to Alternating Current and Transformers. Archived 2006-04-20 at the Way back Machine.