AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
MECHATRONICS DEPARTMENT

Graduation Project Report

3-Axes PCB CNC Machine

Supervised By
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ACKNOWLEDGMENT

We would like to thank and salute everyone who helped, guided and advised us on this project. First, we thank God for our success in this project and its successful completion. Secondly, we extend our thanks and gratitude to Asst. Prof. Omar M.shehata, the main supervisor of this project. And we are extremely grateful for his assistance and guidance throughout this project, his valuable advice made everything simple.

Finally we would like to extend our thanks to our friend and classmate in mechatronics department Eng Maged Noah which was helping us in the all steps of the project starting from buying the materials necessary for the project to the testing stage.

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Abstract

A CNC (Computer Numerical Control) machine uses a stream of digital information which is code from a computer to automatically execute a series of machining operations that CNC machine offer to increase productivity and flexibility. CNC machine also uses mathematics and coordinate systems to process information of what to move, to where and how fast. This machine is able to move in three controlled directions at once which are (X,Y and Z axis).

A CNC machine also must be able to communicate with itself and the machinist to operate. Computer numeric control unit sends position commands to motors. This machine can move very fast in three controlled directions at once to allow them to create almost any desired pattern or shape.

G-code is most widely used in numerical control programming language. It used mainly to control CNC machines and also called G programming language. G-code is a language in which people tell computerized machine tools how to make something.

M-code is a set of instructions executed directly by a computer's central processing unit. Each of the instruction performs a very specific task, such as a load, a jump, or an arithmetic logic unit (ALU) operation on a unit of data in a CPU register or memory. Every program directly executed by a CPU is made of a series of such instructions.

Idea behind this project

Over our study in college we notices that there is no organization or people making professional PCBs using CNC machines which gives a fine quality for the output product and shorten so much time and operations in a single shot, unlike the following traditional way in Egypt which using etching method by cupric chloride Acid to remove the copper layer from the surface of the board then manually drill the holes of the component and manually cut out the board which as predicted consumes too much time and doesn’t give a good look and surface finish for the output product.

But in this project we can do all of this operations in one single step which doesn’t need any human intervention except the installation of the copper sheet in the machine or changing the bit which can also be done automatically by an automatic tool changer (ATC)

And here this project is suitable for production with small to medium quantities.

Note:

This project has the ability to manufacture any material (metal and non-metal) not the PCBs specifically but the main goal of this project is making PCBs

Over all specifications of this project

The required specifications from the project:

-Non cutting speed in x,y directions is 550 mm per minute and 500 mm per minute in the z directions

-Cutting speed for non-metallic and fine metallic materials in x,y directions is 400 mm per minute and 320 mm per minute in the z directions

Note:

The cutting speed is directly affected by the quality and the sharpness of the cutting tool.

-In terms of power consumption the machine should consumes about 3.6 watt for the stepper motors only and max 500 watt for the spindle

-So the total power Consumption is about 1.5 KW per hour

-For the working area:

In X direction 200 mm

In Y direction 150 mm

In Z direction 60 mm

-Spindle max cutting speed is about 9000 rpm

-Output noise doesn’t exceed 90 dB above the existing noise

Main Components of the machine

1. Hardware Components

- **Motors**:

Here we used two types of motors, first type is the Nema 17 Motors which is an open loop stepper motor to control the motion of the X,Y,Z Axes

Working principal

like all with electric motors, stepper motors have a stationary part (the stator) and a moving part (the rotor). On the stator, there are teeth on which coils are wired, while the rotor is either a permanent magnet or a variable reluctance iron core. We will dive deeper into the different rotor structures later. Figure 1 shows a drawing representing the section of the motor is shown, where the rotor is a variable-reluctance iron core.

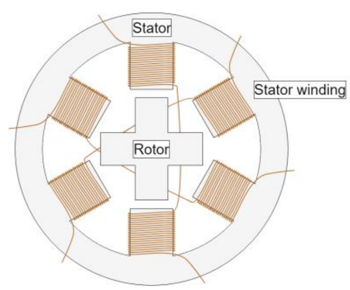


Figure 1 Cross-Section of a Stepper Motor

The basic working principle of the stepper motor is the following: By energizing one or more of the stator phases, a magnetic field is generated by the current flowing in the coil and the rotor aligns with this field. By supplying different phases in sequence, the rotor can be rotated by a specific amount to reach the desired final position. Figure 2 shows a representation of the working principle. At the beginning, coil A is energized and the rotor is aligned with the magnetic field it produces.

When coil B is energized, the rotor rotates clockwise by 60° to align with the new magnetic field. The same happens when coil C is energized. In figure 2, the colors of the stator teeth indicate the direction of the magnetic field generated by the stator winding.

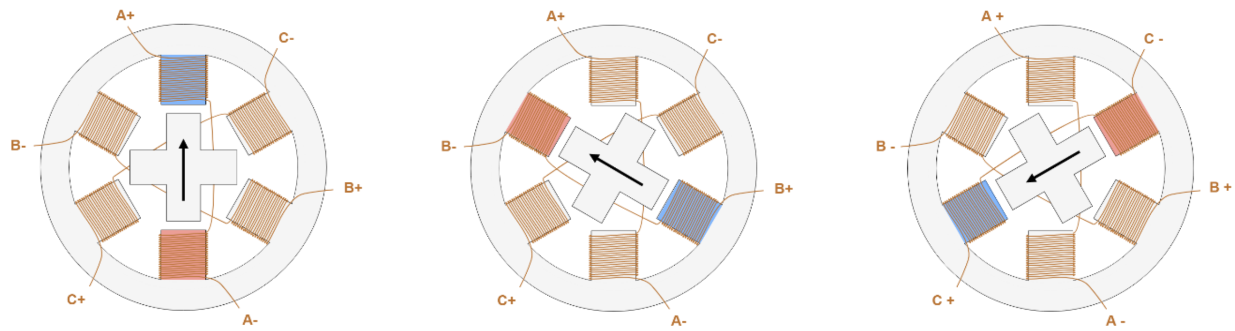


Figure 2 Stepper Motor Steps

The Second one is a Dc Brushed 500W motor used as the main spindle of the machine which used for cutting in the working piece with different speeds according to the need of the operator

Figure 3 500W Spindle

- **Power Supplies**

Here we have two power supplies which are hidden in the control unit, the first one is a 12v-240w power supply used to power all 3 stepper motors and the machine lights

Figure 4 12V Power Supply

Figure 5 12V Power Supply Connections

The Second one is a 36V-500W Power supply which used only to power the spindle

Figure 6 36V Power Supply

- **Stepper motor drivers**

To control the Nema 17 motors we used 3 motor drivers from type A4988

A4988 Stepper Driver Module Features

- Max. Operating Voltage: 35V
- Min. Operating Voltage: 8V
- Max. Current Per Phase: 2A
- Micro-step resolution: Full step, $\frac{1}{2}$ step, $\frac{1}{4}$ step, $\frac{1}{8}$ and $\frac{1}{16}$ step
- Reverse voltage protection: No
- Dimensions: 15.5 × 20.5 mm (0.6″ × 0.8″)
- Short-to-ground and shorted-load protection
- Low RDS(ON) outputs
- Thermal shutdown circuitry

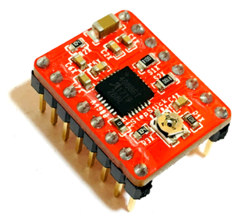


Figure 7 A4988 Driver

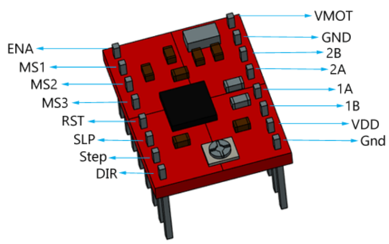


Figure 8 A4988 Pin Out

➢ Control Board

The control board we used is the CNC shield version 3.0 which is an Arduino compatible board that turns the Arduino board into a CNC controller. Using an open source firmware it can control up to 4 Stepper motors using DRV8825 or A4988 stepper motor driver.

Features:

- GRBL 0.8c compatible. (Open source firmware that runs on an Arduino UNO that turns G-code commands into stepper signals).
- 4-Axis support (X, Y, Z , A-Can duplicate X,Y,Z or do a full 4th axis with custom firmware using pins D12 and D13).
- 2 x End stops for each axis (6 in total).
- Spindle enable and direction.
- Coolant enable.
- Uses removable A4988 compatible stepper drivers. (A4988, DRV8825 and others).
- Jumpers to set the Micro-Stepping for the stepper drivers. (Some drivers like the DRV8825 can do up to 1/32 micro-stepping).
- Compact design.
- Stepper Motors can be connected with 4 pin connectors.
- Runs on 12-36V DC. (At the moment only the DRV8825 drivers can handle up to 36V so please consider the operation voltage when powering the board.).

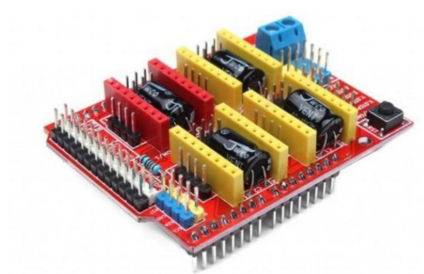


Figure 9 CNC Shield V3.0

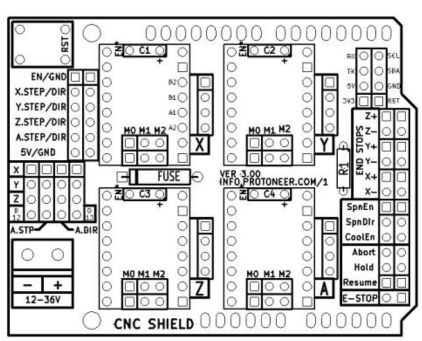


Figure 10 CNC Shield Pin Out

➢ Cutting Tools (Bits)

Here we used different types of bits each one for a special purpose and special operation

- **EndMill**

It's a type of milling cutter, a cutting tool used in industrial milling applications. It is distinguished from the drill bit in its application, geometry, and manufacture. While a drill bit can only cut in the axial direction, most milling bits can cut in the radial direction. Not all mills can cut axially; those designed to cut axially are known as end mills.
End mills are used in milling applications such as profile milling, tracer milling, face milling, and plunging.

Figure 11 PCB EndMill

- **Drillbit**

It is a type of bits that is used to drill holes whatever the diameter is in the work piece

Figure 12 Drillbit

- **BallNose**

Ball nose spiral end mills are used for smooth contouring and fine detail passes with a CNC router and often for complex shapes like 3D carvings. The rounded ends produce smooth curves that would be impossible to achieve with flat end bits. Small diameter ball nose end mills are used for projects with intricate detail while larger bits are used for smoother projects with more gradual slopes. These bits are also excellent for routing fluted columns and channels in cutting boards and countertops edges.

Figure 13 BallNose bit

- **V engraving bit**

Type of cutters used specifically to engrave or to draw on the work piece but it has some other uses like isolating the tracks while making a PCB and used also for finishing in the 3D operations

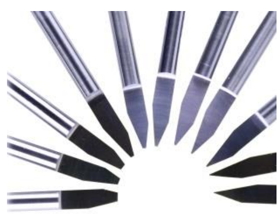


Figure 14 Engraving Bits

- **Mechanical (Movement) parts**

Here we used lots of mechanical parts like linear rail which carry the X axis which considered the heaviest axe in the machine and this rail is fixed on aluminum profile 2020 to main frame and the x Axis moves along the linear rail by a linear guide designed especially for this king of rails

Figure 15 Linear Guide and rail

And for the Y Axis we use a lighter carrying mechanism which is a round soft rod made of stainless steel and a linear bearing to carry the table along the rod because this axis doesn’t carry heavier load like the X axis

Figure 16 Y Carrying Mechanism

PWM Controller

It's used to control the spindle speed manually with a potentiometer

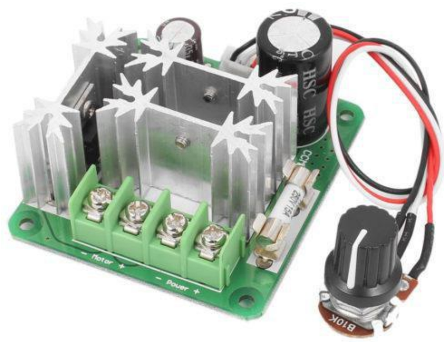


Figure 17 Spindle speed controller

Coupling

The devices that connects the stepper motor shaft to the screw for the purpose of transmitting power and motion, Here we used a rigid coupling instead of the flexible one for the following reasons:

Difference between rigid and flexible coupling:

- Flexible coupling couple with rotating members such as motors and drive shafts, while allowing misalignment in either angular or parallel offset orientation while rigid coupling couple with rotating members such as shafts.
- A rigid coupling is simple and inexpensive while the flexible coupling is comparatively costlier due to additional parts.
- A rigid coupling cannot tolerate misalignment between the axis of shafts used only when there is precise alignment between two shafts while flexible elements like bush or disk can tolerate 0.5^0 of angular misalignment and 5 mm of axial displacement between the shafts.
- The flexible elements in the flexible coupling absorb shocks and vibrations while the motion is free of shocks and vibrations in the rigid coupling.
- Rigid couplings have limited application compared to flexible couplings because rigid couplings do not have the ability to compensate for shaft misalignment and are therefore used where shafts are already positioned in accurate lateral and angular alignment.
- Rigid coupling does not allow for angular or parallel misalignment while flexible coupling does.
- Deflection is less in rigid coupling while flexible coupling has more.

Figure 18 Rigid Coupling

Figure 19 Flexible Coupling

2. Software components:

- **Firmware:**

Here we use GRBL as the firmware which has been uploaded on the Arduino board and it's is a no-compromise, high performance, low cost alternative to parallel-port-based motion control for CNC milling.

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 30 kHz 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.

- **Control programs:**

It has other name and it's G-Coder Sender and its main function is to send the gcode commands to the controller which holds the grbl firmware via a serial communication along some other features like jogging the machine axes ,probing function, visualize the gcode ,…..etc.

Design of the project

Actuator Sizing:

-For the motors which will move the X, Y and Z axes we will choose stepper motor from the Nema series and according to these calculations we find out that the Nema 17 will be fulfill our use requirements.

Calculations for X Axis:

$$J_{screw} = \frac{1}{2}mr^2 = \frac{1}{2} \times 1.5 \times \left(40 \times 10^{-3}\right)^2 = 1.2 \times 10^{-5}\ kg.m^2$$

$$J_{head} = \frac{mp^2}{4\pi^2} = \frac{4.8 \times 4}{4\pi^2} = 0.436\ kg.m^2$$

$$\therefore J_{eff} = 0.43569\ kg.m^2\ , J_{total} = 0.87\ kg.m^2$$

-For Nema 17:

$$T_m = 0.421\ N.m$$

$$\because T_m = J_{Total}\,\ddot{\theta} \quad \rightarrow\rightarrow \therefore\ \ddot{\theta} = 0.483\ rad\ /\ sec$$

$$\because F = \frac{2\pi \times T_m}{2} = \frac{2\pi \times 0.421}{2} = 1.323\ N$$

-For Nema 23:

$$T_m = 1.863\ N.m$$

$$\because T_m = J_{Total}\,\ddot{\theta} \quad \rightarrow\rightarrow \therefore\ \ddot{\theta} = 2.14\ rad\ /\ sec$$

$$\because F = \frac{2\pi \times T_m}{2} = \frac{2\pi \times 1.863}{2} = 5.85\ N$$

-According to the previous calculations we chose Nema 17

Note:

These calculations applies for Y Axis too cause the x axis is heavier than the y axis

Calculations for Z Axis:

$$J_{screw} = \frac{1}{2}mr^2 = \frac{1}{2} \times 1.5 \times \left(40 \times 10^{-3}\right)^2 = 1.2 \times 10^{-5}\ kg.m^2$$

$$J_{head} = \frac{mp^2}{4\pi^2} = \frac{2 \times 4}{4\pi^2} = 0.2026\ kg.m^2$$

$$\therefore J_{eff} = 0.203\ kg.m^2\ , J_{total} = 0.406\ kg.m^2$$

-For Nema 17:

$$T_m = 0.421\ N.m$$

$$\because T_m = J_{Total}\,\ddot{\theta} \quad \rightarrow\rightarrow \therefore\ \ddot{\theta} = 1.037\ rad\ /\ sec$$

$$\because F = \frac{2\pi \times T_m}{2} = \frac{2\pi \times 0.421}{2} = 1.323\ N$$

-According to the previous calculations we chose Nema 17

-For the spindle we chose the 500 watt version as it was available for us to use and with this high amount of power comes high amount of RPM and reasonable amount of stall torque for the spindle which will eventually leads to high cutting speed with good and smooth surface finish for the product either PCB, wood, acrylic …. Etc.

Designing on the solidWorks:

-For the main frame we choose 3 mm thick steel sheets which will be cut by fiber laser CNC machine to achieve the desired shape and then assembling all the parts together to get the final shape of the machine

Here are some images from the designing process on solidWorks:

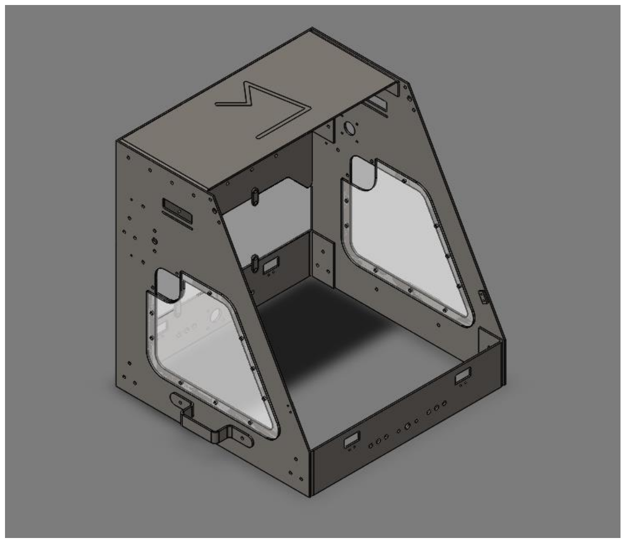


Figure 20 Main frame of the machine

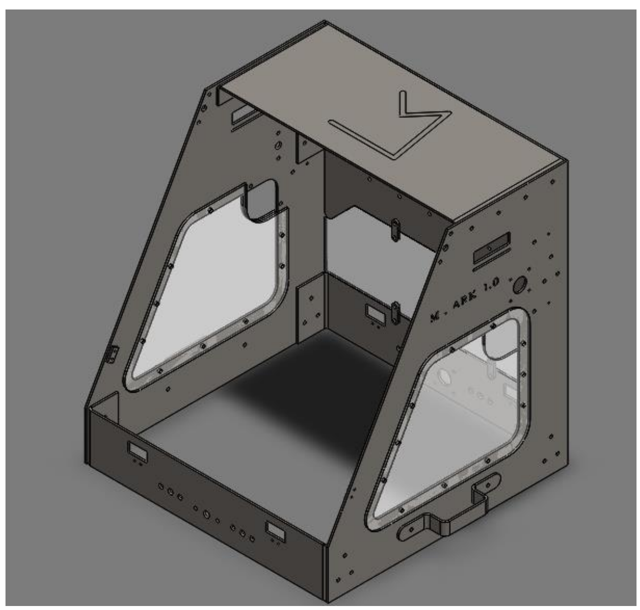


Figure 21 Main frame of the machine

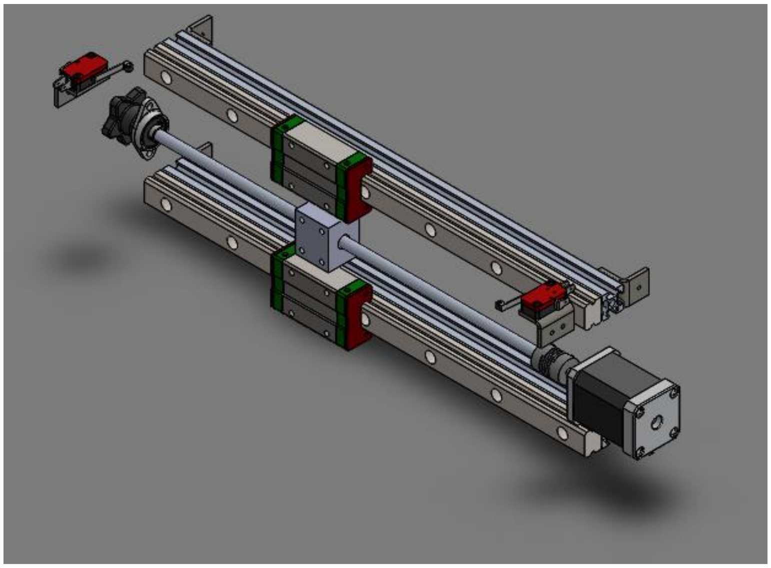


Figure 22 X Axis Mechanism

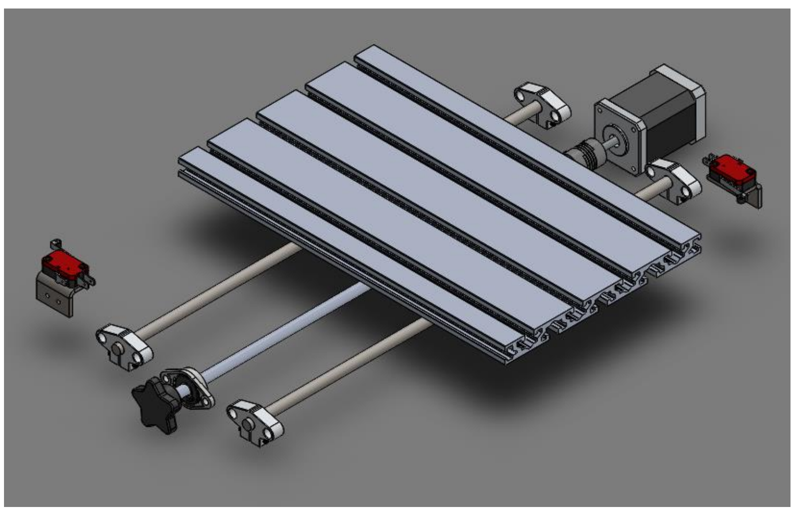


Figure 23 Y Axis Mechanism

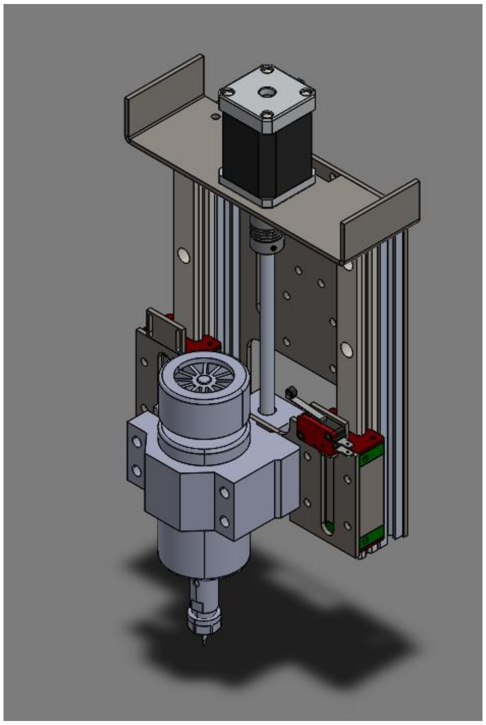


Figure 24 Z Axis Mechanism

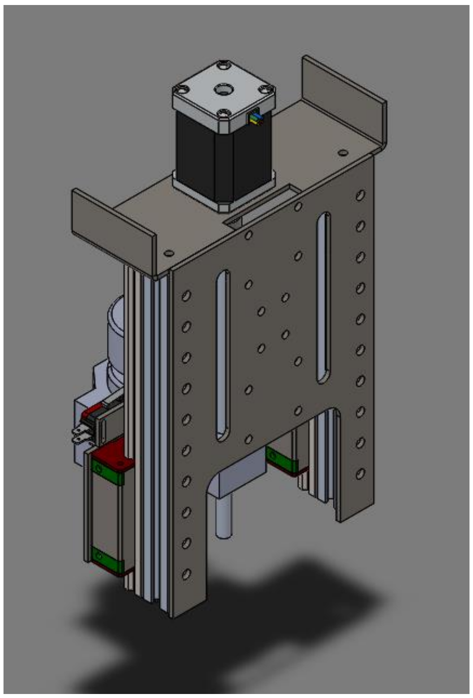


Figure 25 Z Axis Mechanism

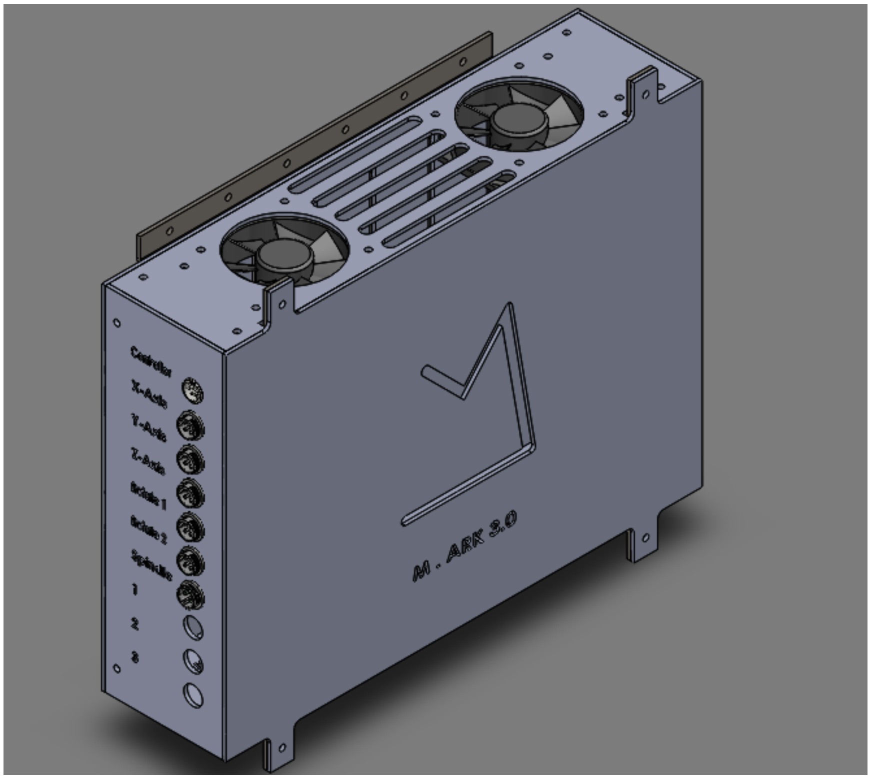


Figure 26 Machine Control Unit

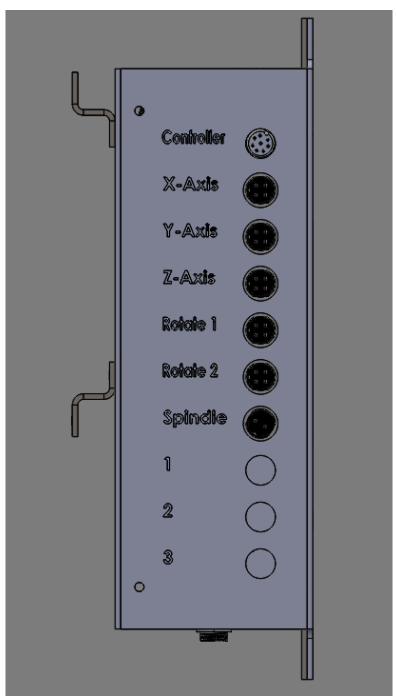


Figure 27 Control Unit Axes Side

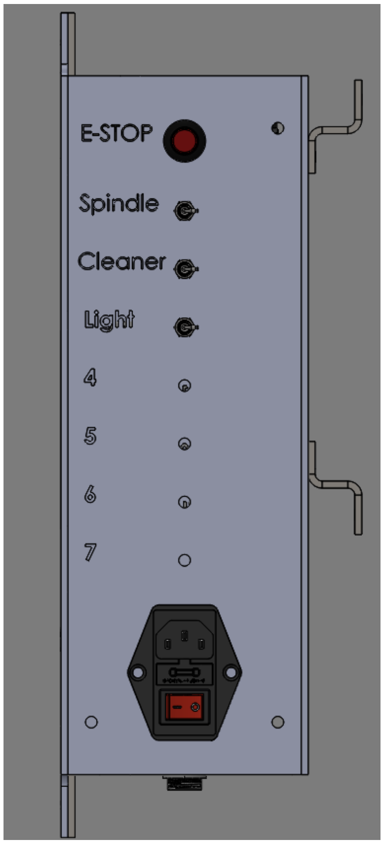


Figure 28 Control Unit Switches Side

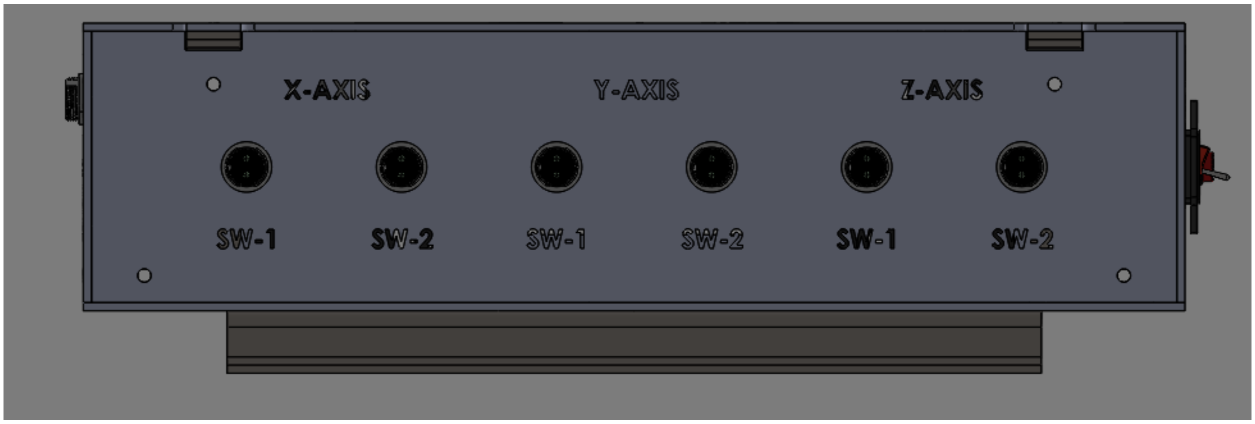


Figure 29 Control Unit Limit switches Side

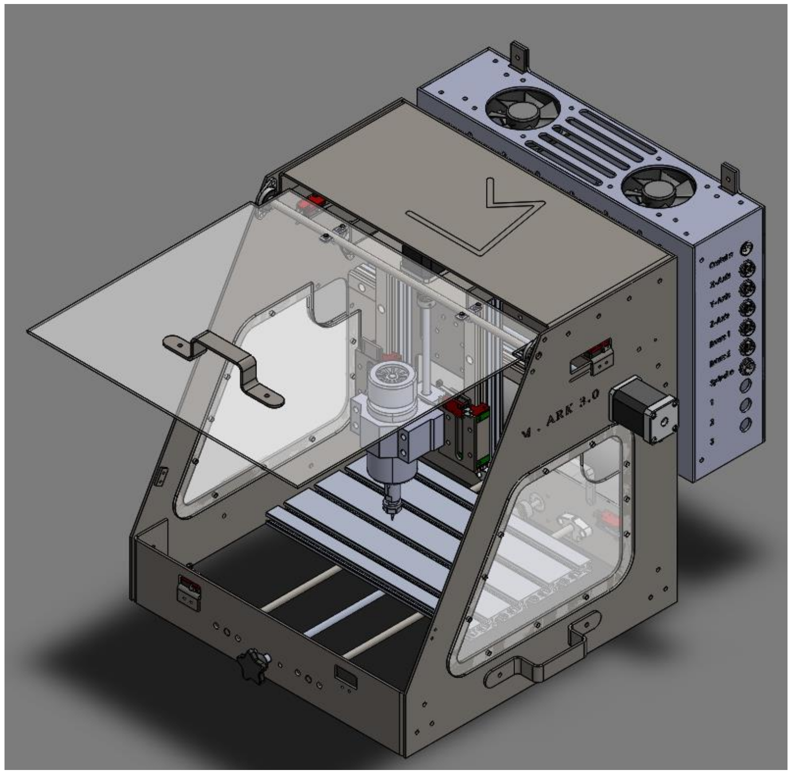


Figure 30 the Whole Machine

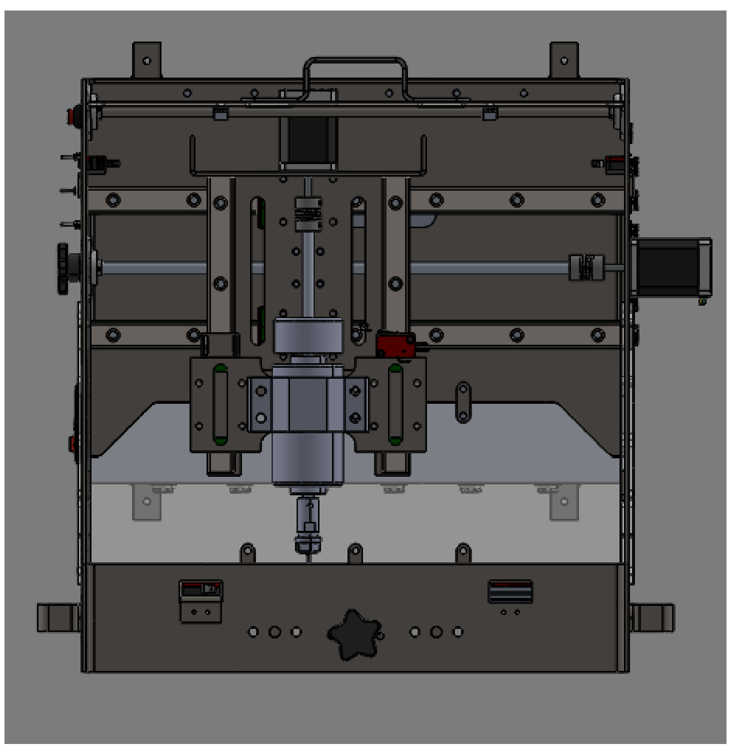


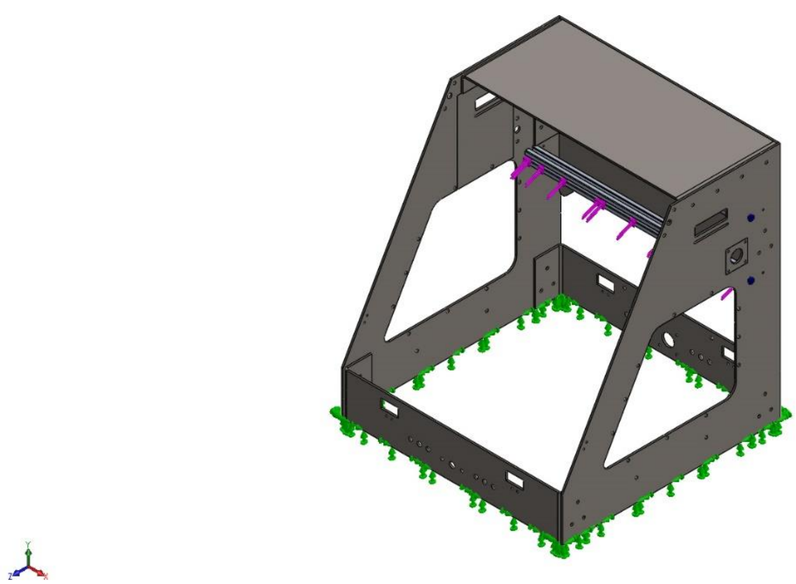
Figure 31the Whole Machine

Simulation on SolidWorks:

-For the Simulation part we only simulate the result of impact force on the main frame and how it will affect its consistency to prevent this force from transferring to the internal solid or moving parts of the machine and to prevent the vibrations coming from the motors or the spindle to transfer it out of the main body of the machine.

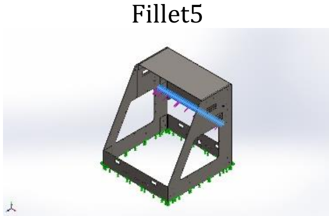
- **Simulation of the vibrations on the main frame**

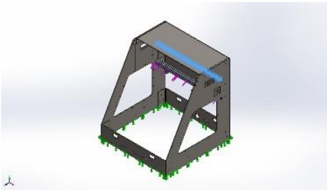
Model Information



Model name: Frame Assembly(For Simulation)
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Fillet5 	Solid Body	Mass:0.185179 kg Volume:6.85848e-05 m^3 Density:2700 kg/m^3 Weight:1.81475 N	F:\Grad.CNC\5 Axis CNC\5 Axis CNC\Aluminum Profiles\2020\2020 alu section.SLDPRT Feb 12 01:18:18 2022

Fillet5 	Solid Body	Mass:0.185179 kg Volume:6.85848e-05 m^3 Density:2700 kg/m^3 Weight:1.81475 N	F:\Grad.CNC\5 Axis CNC\5 Axis CNC\Aluminum Profiles\2020\2020 alu section.SLDPRT Feb 12 01:18:18 2022

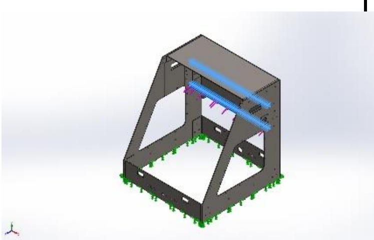
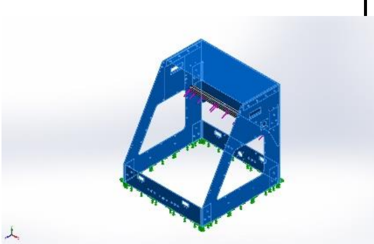
Study Properties

Study name	Static 4 from [Static 3 from [head impact force from [Static 1]]]
Analysis type	Static
Mesh type	Mixed Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (F:\Grad.CNC\5-Axis-CNC-master\5-Axis-CNC-master\Main Assembly\Simulation)

Units

Unit system:	SI (MKS)
Length/Displacement	m
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

Model Reference	Properties	Components
	Name: **1060 Alloy** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.75742e+07 N/m^2** Tensile strength: **6.89356e+07 N/m^2** Elastic modulus: **6.9e+10 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3** Shear modulus: **2.7e+10 N/m^2** Thermal expansion coefficient: **2.4e-05 /Kelvin**	**SolidBody 1(Fillet5)(2020 alu section-1), SolidBody 1(Fillet5)(2020 alu section-3)**
Curve Data:N/A		
	Name: **Wrought Stainless Steel** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.06807e+08 N/m^2** Tensile strength: **5.17017e+08 N/m^2** Elastic modulus: **2e+11 N/m^2** Poisson's ratio: **0.26** Mass density: **8000 kg/m^3** Shear modulus: **7.9e+10 N/m^2** Thermal expansion coefficient: **1.1e-05 /Kelvin**	**SolidBody 1(Cut-Extrude3)(Back_Support_Top-1), SolidBody 1(Cut-Extrude1)(Roof_Support-2), SolidBody 1(Split Line1)(X_Bearing_Side-1), SolidBody 1(Split Line1)(X_Stepper_Side-1), SolidBody 1(Cut-Extrude4)(Y_Bearing_Side-2), SolidBody 1(Cut-Extrude5)(Y_Stepper_Side-1)**
Curve Data:N/A		

Loads and Fixtures

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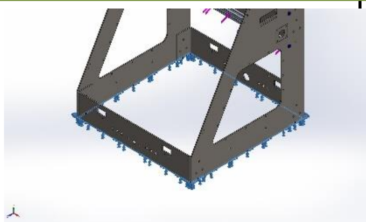
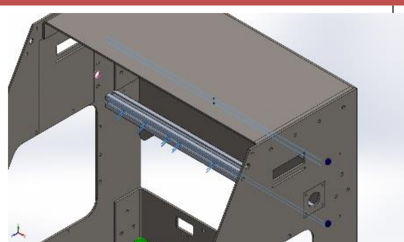
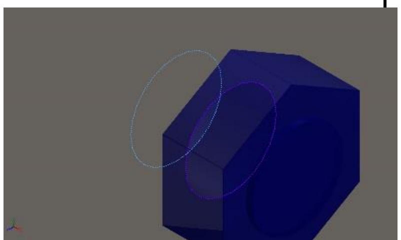
Fixed-1		**Entities:** **12 face(s)** **Type:** **Fixed Geometry**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-4.17233e-07	-65.6947	-67.8341	94.4312
Reaction Moment(N.m)	0.00252232	-0.000122636	0.00106753	0.00274167

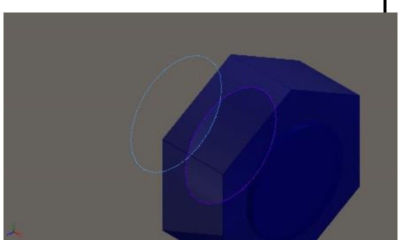
Load name	Load Image	Load Details
Torque-1		**Entities:** **3 face(s)** **Reference:** **Face< 1 >** **Type:** **Apply torque** **Value:** **3.5 N.m**

Connector Definitions

Model Reference	Connector Details	Strength Details
 Counterbore with Nut-1	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005** Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	**No Data**

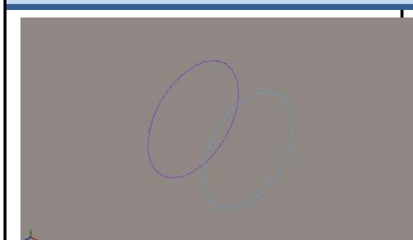
Connector Forces

Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	-122.49	0	0	122.49
Shear Force (N)	0	7.7516	-21.678	23.023
Bending moment (N.m)	0	-0.02862	0.003903	0.028885

Model Reference	Connector Details	Strength Details
 Counterbore with Nut-2	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005** Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	**No Data**

Connector Forces

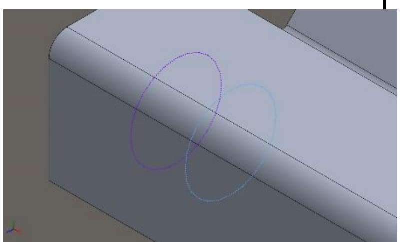
Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	-225.48	0	0	225.48
Shear Force (N)	0	11.244	32.642	34.525
Bending moment (N.m)	0	0.058599	-0.0014615	0.058617

Model Reference	Connector Details	Strength Details
 Counterbore with Nut-3	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005**	**No Data**

	Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	

Connector Forces

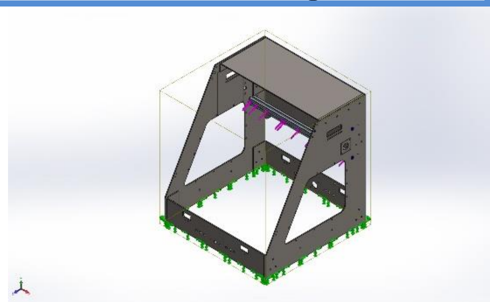
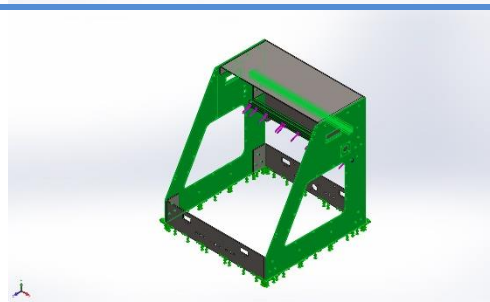
Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	**318.05**	**0**	**0**	**318.05**
Shear Force (N)	**0**	**34.46**	**56.05**	**65.796**
Bending moment (N.m)	**0**	**-0.076334**	**-0.0090403**	**0.076868**

 Counterbore with Nut-4	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005** Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	**No Data**

Connector Forces

Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	**124.15**	**0**	**0**	**124.15**
Shear Force (N)	**0**	**5.7576**	**-19.48**	**20.313**
Bending moment (N.m)	**0**	**0.029455**	**0.0048439**	**0.029851**

Contact Information

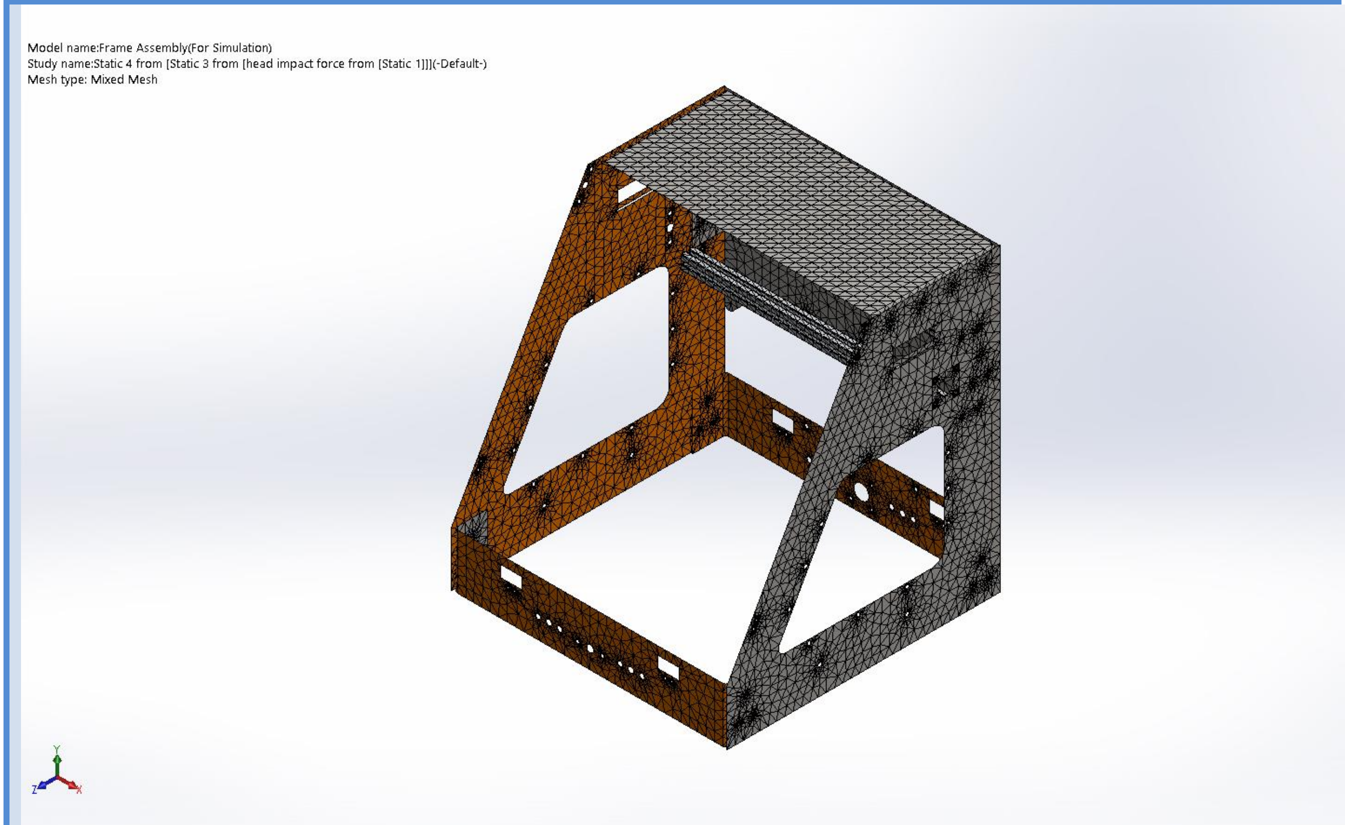
Contact	Contact Image	Contact Properties
Global Contact		**Type:** Bonded **Components:** 1 component(s) **Options:** Compatible mesh
Component Contact-1		**Type:** No penetration (Surface to surface) **Components:** 1 component(s), 3 Solid Body (s)

Mesh information

Mesh type	Mixed Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Jacobian check for shell	On
Element Size	12.375 mm
Tolerance	0.618749 mm
Mesh Quality Plot	High
Remesh failed parts with incompatible mesh	Off

Mesh information - Details

Total Nodes	55130
Total Elements	27650
Time to complete mesh(hh;mm;ss):	00:00:51
Computer name:	



Resultant Forces:

Reaction forces

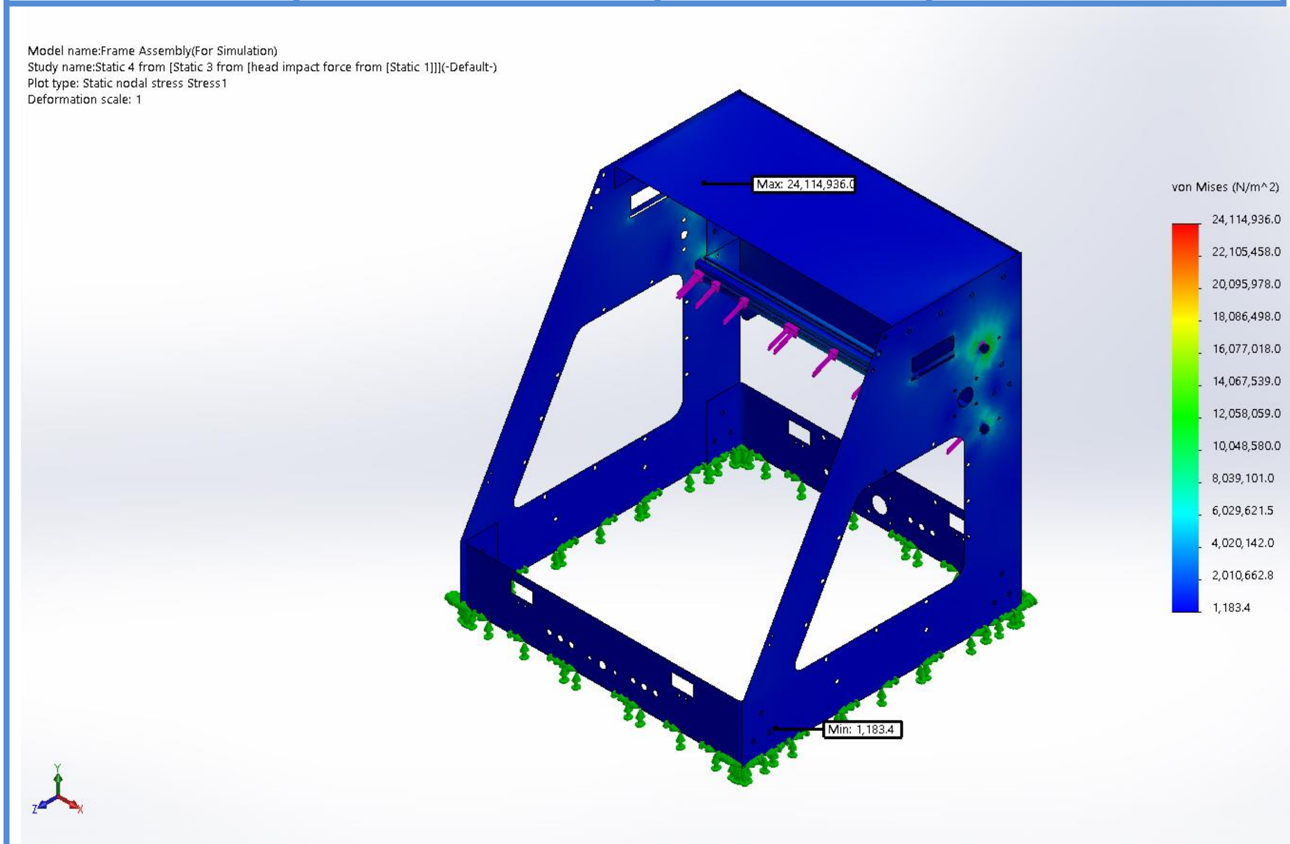
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-4.17233e-07	-65.6947	-67.8341	94.4312

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0.00252232	-0.000122636	0.00106753	0.00274167

Study Results

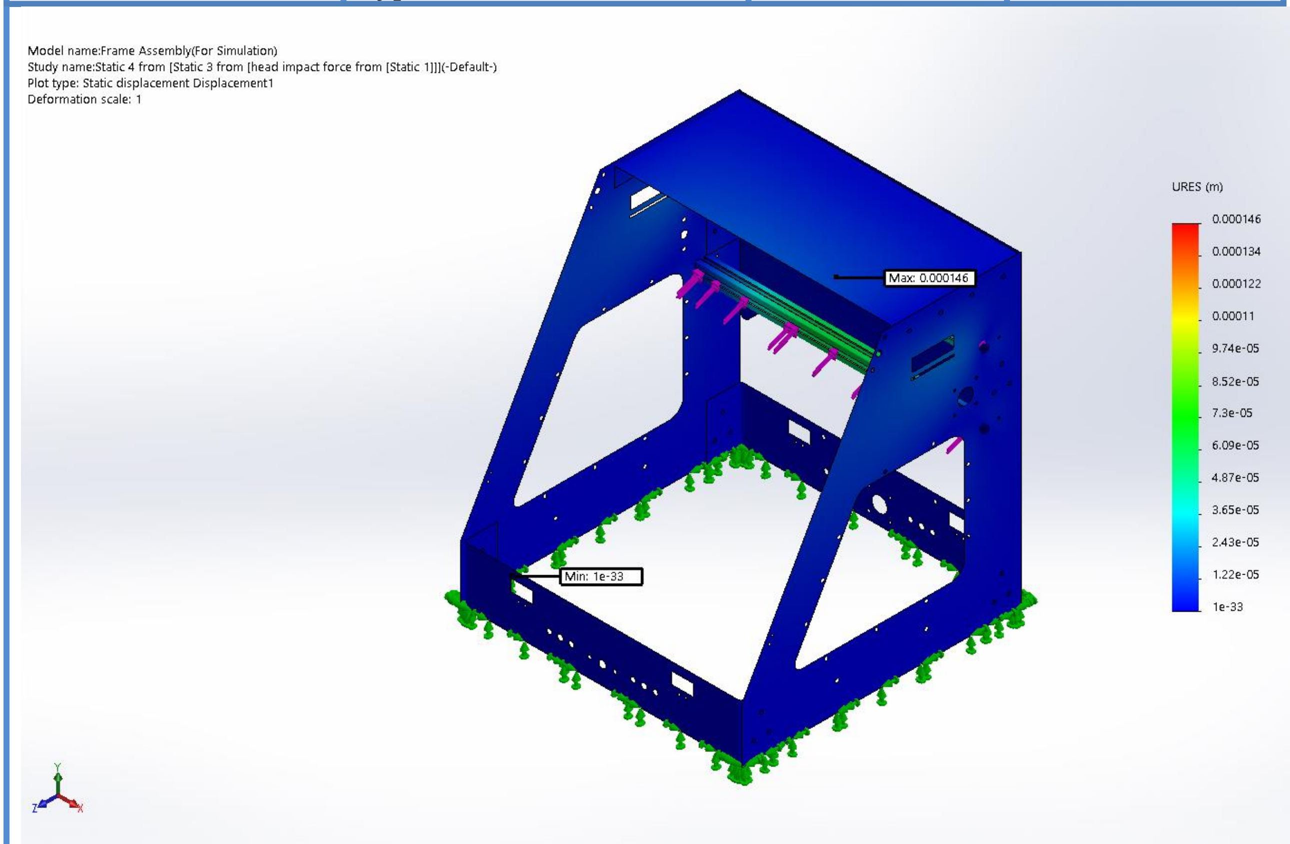
Name	Type	Min	Max
Stress1	VON: von Mises Stress	1,183.4 N/m^2 Node: 49148	24,114,936.0N/m^2 Node: 33949



Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 m Node: 34488	0.000146 m Node: 16647

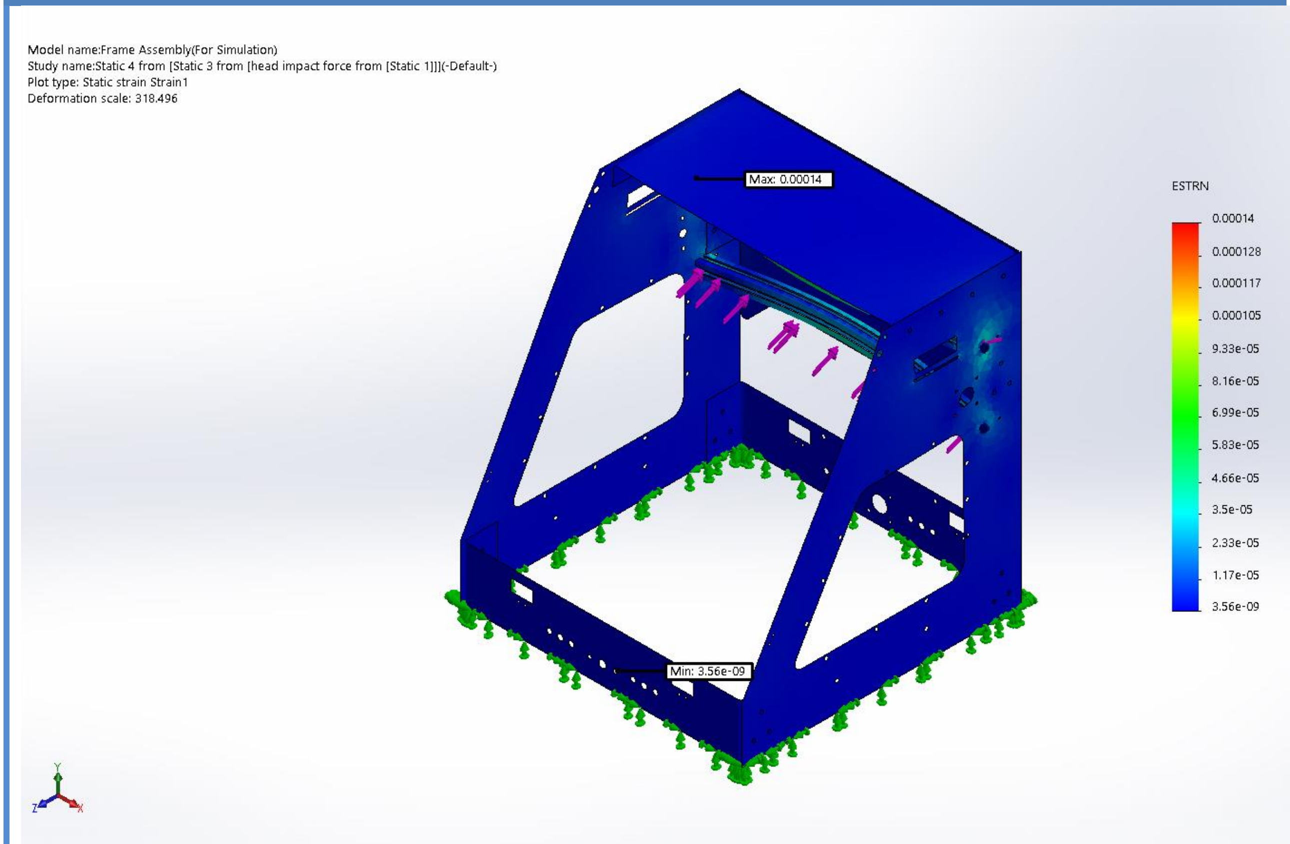
Name	Type	Min	Max



Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.56e-09 Element: 25157	0.00014 Element: 9569

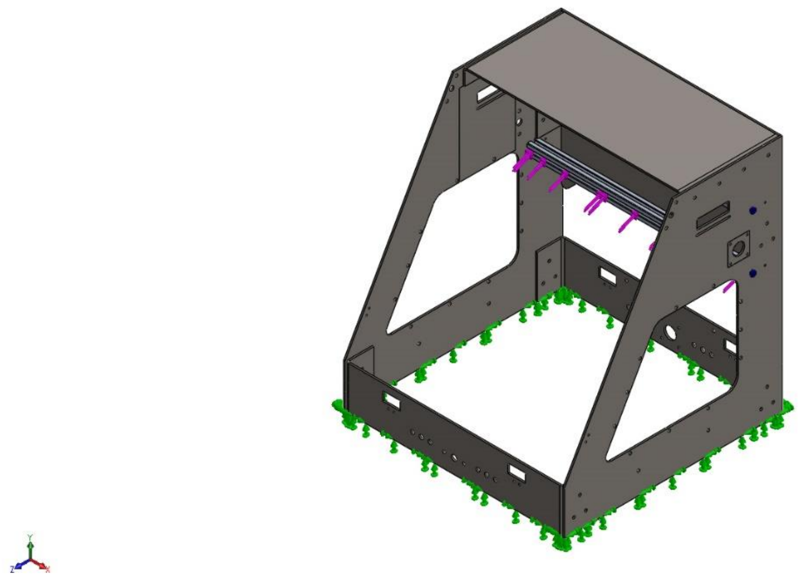
Name	Type	Min	Max



Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Strain-Strain1

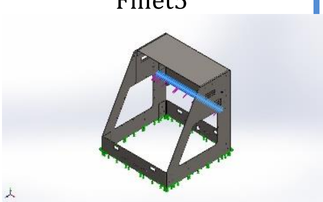
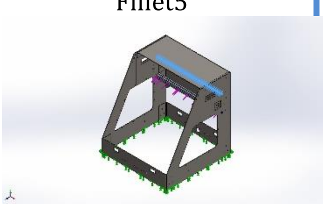
- **The effect of the impact results from the head moving with its max speed towards the frame**

Model Information



Model name: Frame Assembly(For Simulation)
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Fillet5 	Solid Body	Mass:0.185179 kg Volume:6.85848e-05 m^3 Density:2700 kg/m^3 Weight:1.81475 N	F:\Grad.CNC\5 Axis CNC\5 Axis CNC\Aluminum Profiles\2020\2020 alu section.SLDPRT Feb 12 01:18:18 2022
Fillet5 	Solid Body	Mass:0.185179 kg Volume:6.85848e-05 m^3 Density:2700 kg/m^3 Weight:1.81475 N	F:\Grad.CNC\5 Axis CNC\5 Axis CNC\Aluminum Profiles\2020\2020 alu section.SLDPRT Feb 12 01:18:18 2022

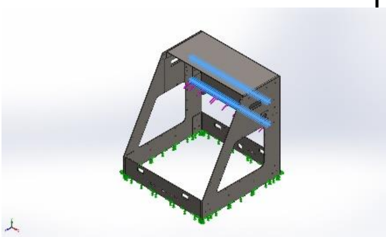
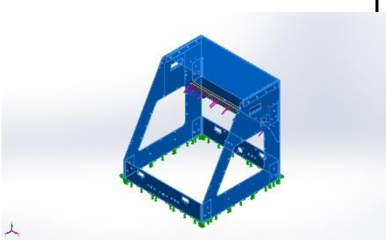
Study Properties

Study name	Static 4 from [Static 3 from [head impact force from [Static 1]]]
Analysis type	Static
Mesh type	Mixed Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (F:\Grad.CNC\5-Axis-CNC-master\5-Axis-CNC-master\Main Assembly\Simulation)

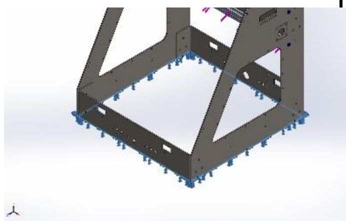
Units

Unit system:	SI (MKS)
Length/Displacement	m
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

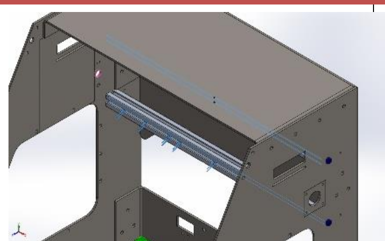
Model Reference	Properties	Components
	Name: **1060 Alloy** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.75742e+07 N/m^2** Tensile strength: **6.89356e+07 N/m^2** Elastic modulus: **6.9e+10 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3** Shear modulus: **2.7e+10 N/m^2** Thermal expansion coefficient: **2.4e-05 /Kelvin**	**SolidBody 1(Fillet5)(2020 alu section-1),** **SolidBody 1(Fillet5)(2020 alu section-3)**
Curve Data:N/A		
	Name: **Wrought Stainless Steel** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.06807e+08 N/m^2** Tensile strength: **5.17017e+08 N/m^2** Elastic modulus: **2e+11 N/m^2** Poisson's ratio: **0.26** Mass density: **8000 kg/m^3** Shear modulus: **7.9e+10 N/m^2** Thermal expansion coefficient: **1.1e-05 /Kelvin**	**SolidBody 1(Cut-Extrude3)(Back_Support_Top-1),** **SolidBody 1(Cut-Extrude1)(Roof_Support-2),** **SolidBody 1(Split Line1)(X_Bearing_Side-1),** **SolidBody 1(Split Line1)(X_Stepper_Side-1),** **SolidBody 1(Cut-Extrude4)(Y_Bearing_Side-2),** **SolidBody 1(Cut-Extrude5)(Y_Stepper_Side-1)**
Curve Data:N/A		

Loads and Fixtures

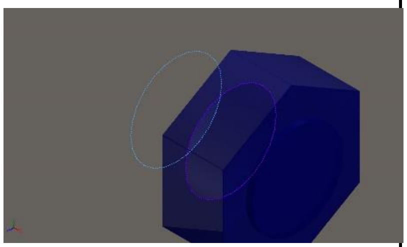
Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** **12 face(s)** **Type:** **Fixed Geometry**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-4.17233e-07**	**-65.6947**	**-67.8341**	**94.4312**
Reaction Moment(N.m)	**0.00252232**	**-0.000122636**	**0.00106753**	**0.00274167**

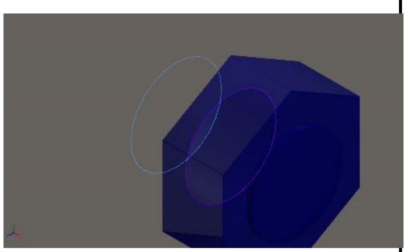
Load name	Load Image	Load Details
Torque-1		**Entities:** **3 face(s)** **Reference:** **Face< 1 >** **Type:** **Apply torque** **Value:** **3.5 N.m**

Connector Definitions

Model Reference	Connector Details	Strength Details
 Counterbore with Nut-1	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005** Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	**No Data**

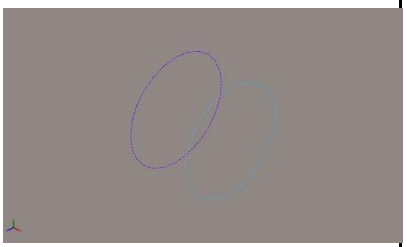
Connector Forces

Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	-122.49	0	0	122.49
Shear Force (N)	0	7.7516	-21.678	23.023
Bending moment (N.m)	0	-0.02862	0.003903	0.028885

Model Reference	Connector Details	Strength Details
 Counterbore with Nut-2	Entities: **2 edge(s)** Type: **Bolt(Head/Nut diameter)(Counterbore)** Head diameter: **0.0075 m** Nut diameter: **0.0075 m** Nominal shank diameter: **0.005** Preload (Torque): **0** Young's modulus: **2.1e+11** Poisson's ratio: **0.28** Preload units: **N.m**	**No Data**

Connector Forces

Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	-225.48	0	0	225.48
Shear Force (N)	0	11.244	32.642	34.525
Bending moment (N.m)	0	0.058599	-0.0014615	0.058617

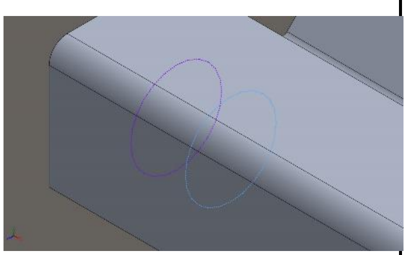

Counterbore with Nut-3

Entities:	2 edge(s)
Type:	Bolt(Head/Nut diameter)(Counterbore)
Head diameter:	0.0075 m
Nut diameter:	0.0075 m
Nominal shank diameter:	0.005
Preload (Torque):	0
Young's modulus:	2.1e+11
Poisson's ratio:	0.28
Preload units:	N.m

No Data

Connector Forces

Type	X-Component	Y-Component	Z-Component	Resultant
Axial Force (N)	318.05	0	0	318.05
Shear Force (N)	0	34.46	56.05	65.796
Bending moment (N.m)	0	-0.076334	-0.0090403	0.076868

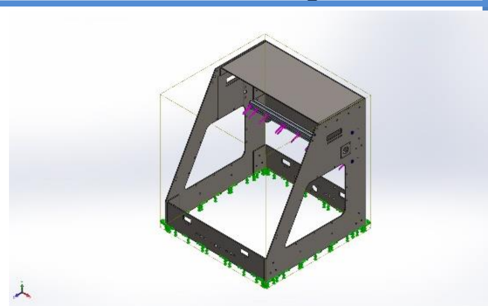
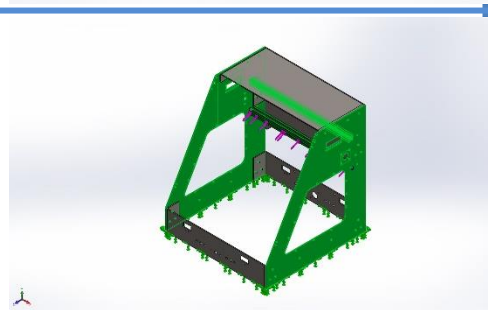

Counterbore with Nut-4

Entities:	2 edge(s)
Type:	Bolt(Head/Nut diameter)(Counterbore)
Head diameter:	0.0075 m
Nut diameter:	0.0075 m
Nominal shank diameter:	0.005
Preload (Torque):	0
Young's modulus:	2.1e+11
Poisson's ratio:	0.28
Preload units:	N.m

No Data

Connector Forces				
Type	**X-Component**	**Y-Component**	**Z-Component**	**Resultant**
Axial Force (N)	**124.15**	**0**	**0**	**124.15**
Shear Force (N)	**0**	**5.7576**	**-19.48**	**20.313**
Bending moment (N.m)	**0**	**0.029455**	**0.0048439**	**0.029851**

Contact Information

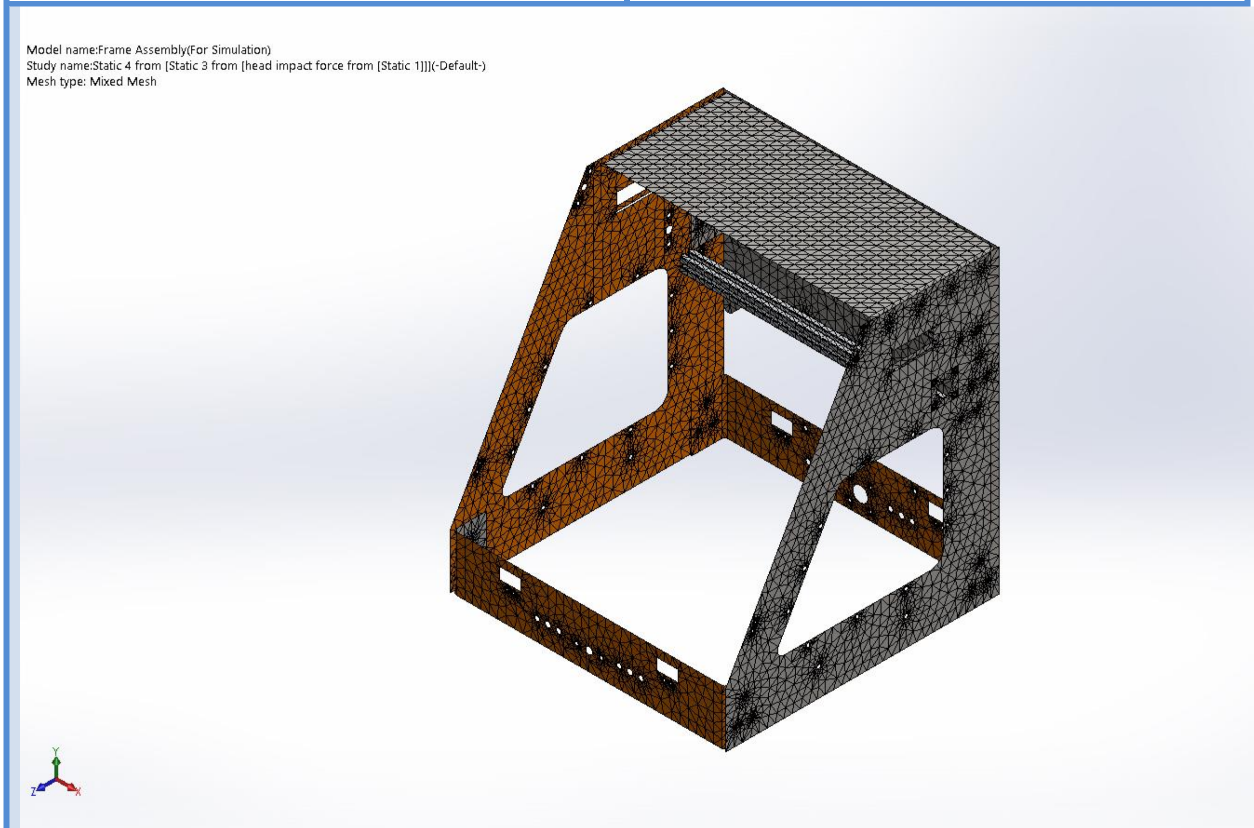
Contact	Contact Image	Contact Properties
Global Contact		**Type:** Bonded **Components:** 1 component(s) **Options:** Compatible mesh
Component Contact-1		**Type:** No penetration (Surface to surface) **Components:** 1 component(s), 3 Solid Body (s)

Mesh information

Mesh type	Mixed Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Jacobian check for shell	On
Element Size	12.375 mm
Tolerance	0.618749 mm
Mesh Quality Plot	High
Remesh failed parts with incompatible mesh	Off

Mesh information – Details

Total Nodes	55130
Total Elements	27650
Time to complete mesh(hh;mm;ss):	00:00:51
Computer name:	



Resultant Forces:

Reaction forces

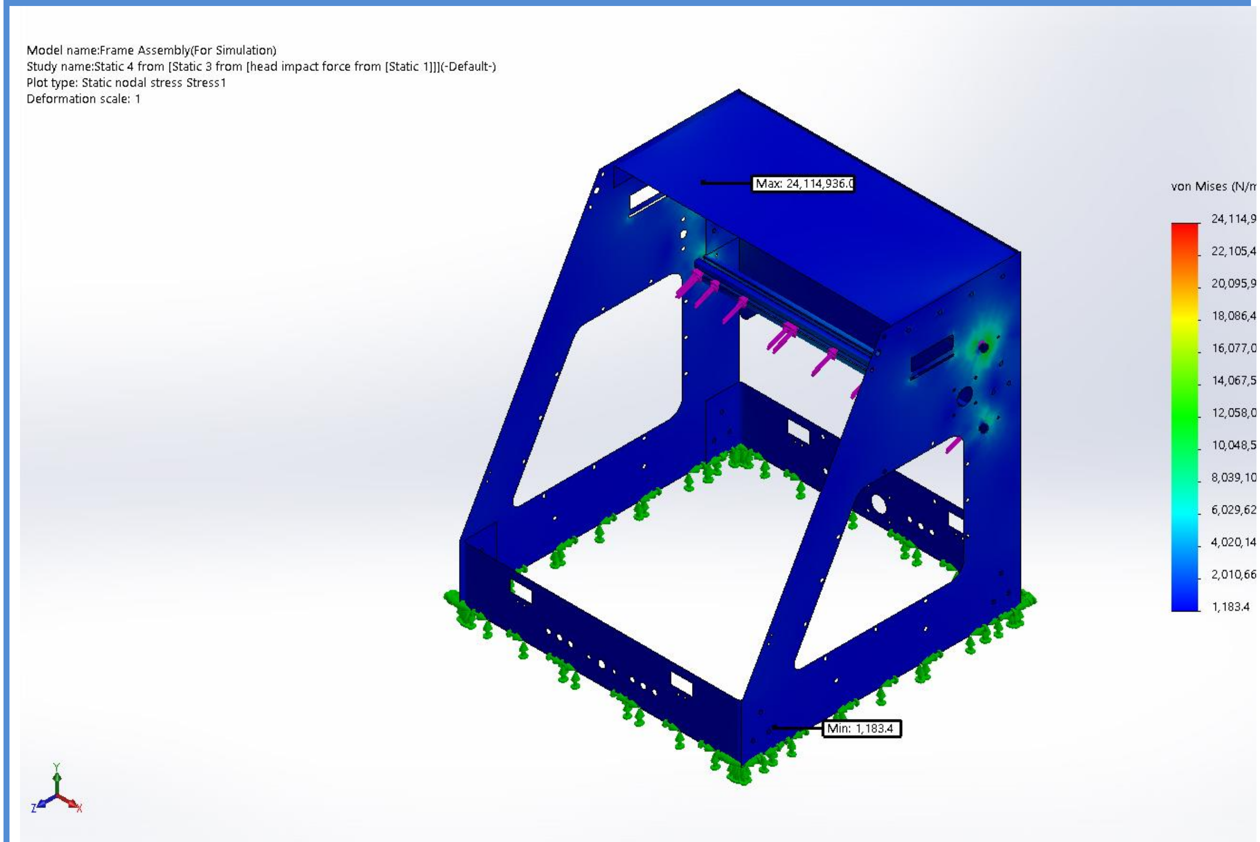
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-4.17233e-07	-65.6947	-67.8341	94.4312

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0.00252232	-0.000122636	0.00106753	0.00274167

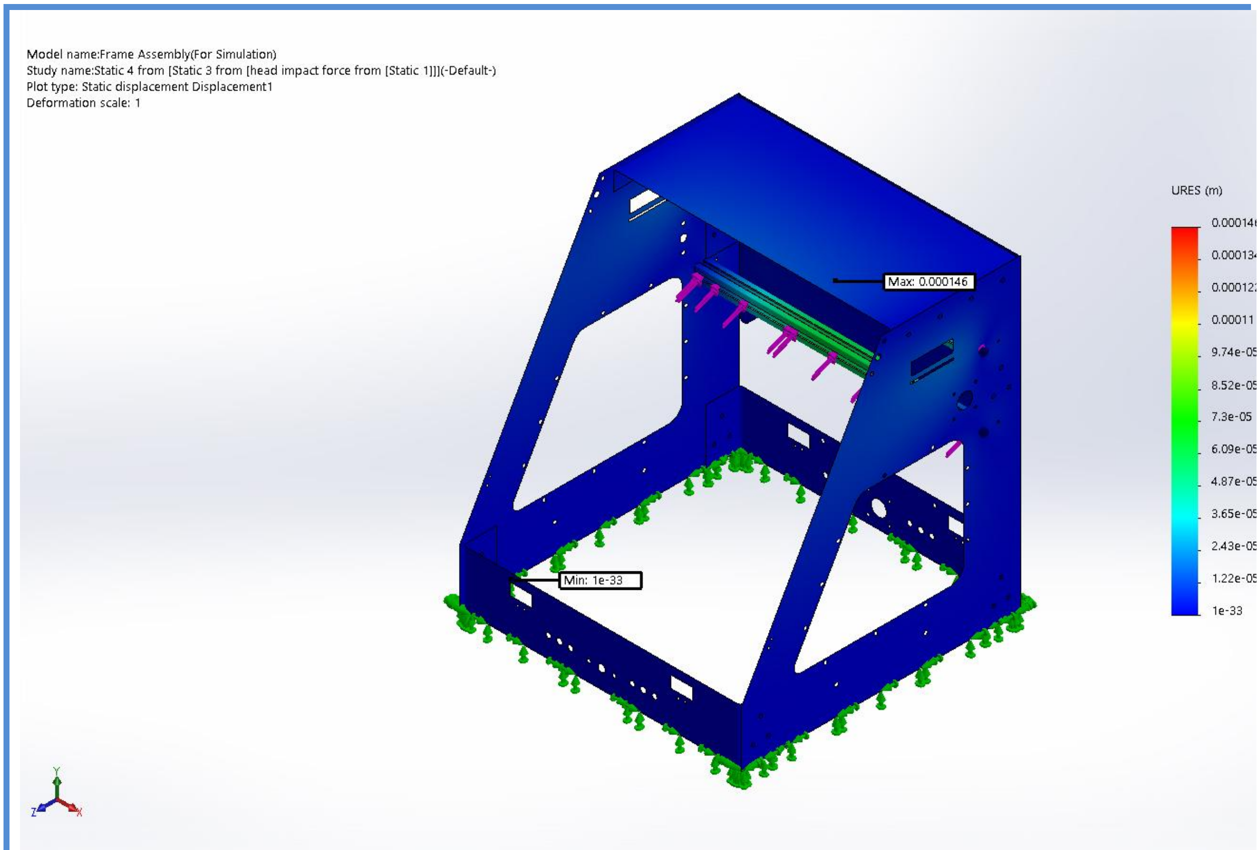
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	1,183.4 N/m^2 Node: 49148	24,114,936.0N/m^2 Node: 33949



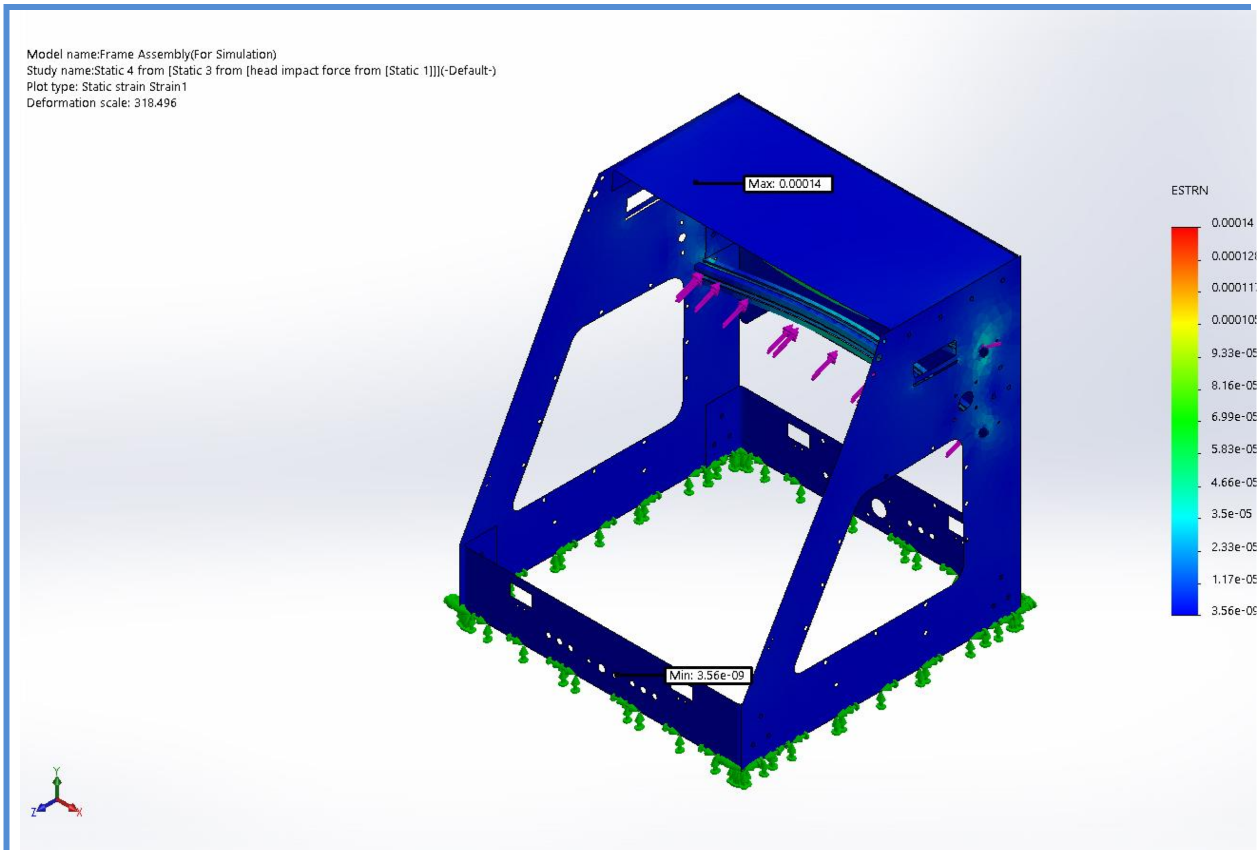
Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 m Node: 34488	0.000146 m Node: 16647



Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.56e-09 Element: 25157	0.00014 Element: 9569



Frame Assembly(For Simulation)-Static 4 from [Static 3 from [head impact force from [Static 1]]]-Strain-Strain1

Assembled machine:

-After the manufacturing of most of the parts of the machine and assemble it.

Figure 32 Assembled frame

Figure 33 Assembled fame

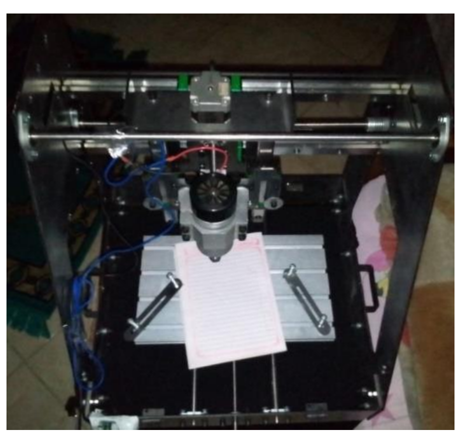


Figure 34 Assembled machine

Problems appeared after the tests:

-After assembling the machine and attaching the spindle we began testing to make sure that everything runs smoothly and correctly and we then began tuning the best GRBL parameters for the machine, in this stage too a lot of errors and fails appeared in the machine both in the design or the motion that we didn't notice it in the design stage.

1. Distortions in circles or curves

After some tests and making some samples we noticed that the circles and curves came out distorted but when we tried drawing lines it came out perfect in terms of length and straightness

Figure 35 Circle Distortion

Figure 36 Circle Distortion

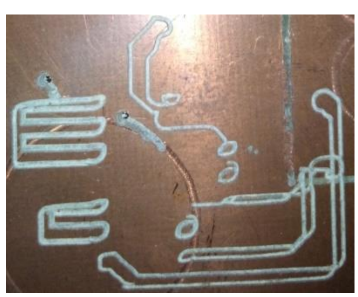


Figure 37 Distortion in PCB tracks

-At this point we thought that the problem occurred as a result of the vibrations from the spindle while cutting in the material or incompatibility between the feedrate and the cutting speed of the spindle so we replace our debugging way by replacing the bit by a pin tip and start to draw circles and curves again

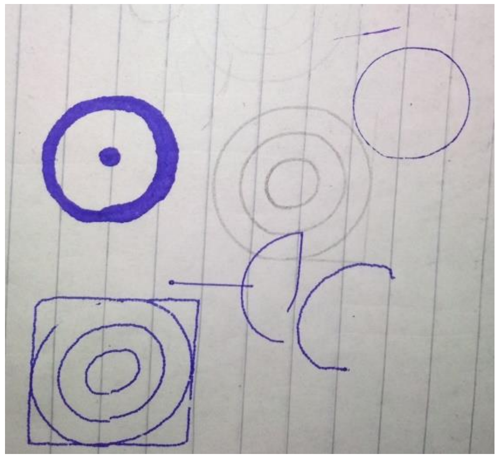


Figure 38 Circles and Curves Distortion

-After the last modification we concluded that the problem wasn't in the spindle or resultant from the spindle or resultant from the vibrations so we went to replace the X and Y motors (because we used old motors) by brand new motors but the problem still exists.

-After running some other tests and some modification in the hardware and software side we concluded that the problem was caused by the flexible coupling connecting the motor and the screw

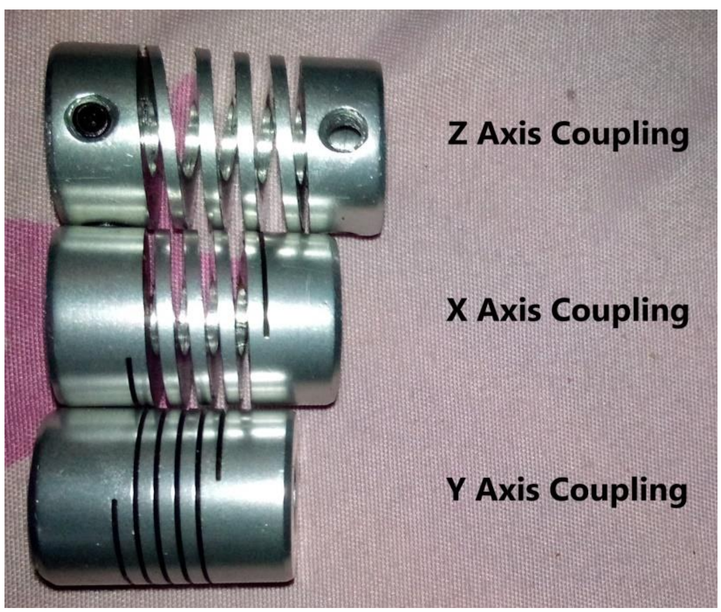


Figure 39 X, Y, Z Couplings

2. Loud noises and vibrations coming from Nema 17

-There was weird a loud noise coming from the driving motors (Nema 17) accompanied by strong vibrations in the frame and the whole machine so strong so that the bolts and nuts are getting loose.

-And surely this problem affects the quality of the output product especially the PCBs

3. Not Knowing the exact height between the end of the bit and the material surface (z zero)

-To start machining the work piece wood, acrylic, PCBs the location of the working zero must be defined before the machine start working.

-X, Y coordinates can be locate in any location on the work piece according to the design but the Z coordinate must be (most of the causes especially the PCBs) on the top of the material, so we could lower the Z axis bit by bit till it in made contact with the material surface from the operating person point of view which always have a very big error and when it comes to working on PCBs this error makes the bit either cuts deep in the PCB or only scratch the surface.

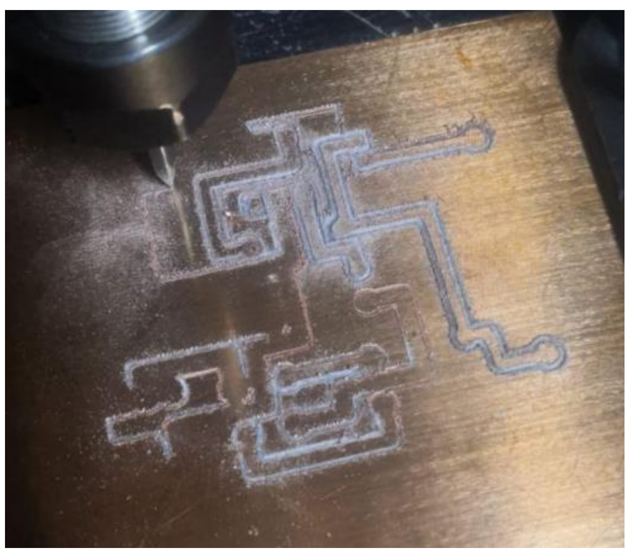


Figure 40 Extra depth result on the PCB

4. Uneven surface for the PCB

-After making some PCBs we noticed that all the raw PCBs have an amount of surface lever inequality due to the manufacturing process and this problem leads to the bit cuts in certain area on the surface of the PCB and barley scratch the other parts of the PCB s other normal Z probing will not work in this case and we need some kind of height map of the surface of the PCB to neutralize this error

How we solved these problems:

1. Distortions in circles or curves solution

The solution of this problem is to replace the flexible coupling with rigid one

2. Loud noises and vibrations coming from Nema 17 solution

Here we solve this problem by Appling the micro stepping concept which is a method of moving the stator plug of the stepper motor more smoothly than it is in the full or half step drive mode. The process of micro stepping helps in reducing the vibration and produces noiseless stepping as low as 0 Hz. It even makes the step angle smaller and the positioning becomes much better.

- **Advantages of micro stepping**
  -Reduced mechanical noise
  -Reduced vibration problem
  -Gentle mechanical actuation

3. Not Knowing the exact height between the end of the bit and the material surface (z zero) solution

To solve this problem we use the probe function that Grbl firmware provides it which makes the Axis (Z Axis in this case) searching automatically for the material surface and either stop on contact or retract a predefined distance from the surface.

This function used for metallic and nonmetallic materials

4. Uneven surface for the PCB solution

The solution of this problem is a software solution since there is no practical solution to ensure the copper layer on the PCB evenly distrusted on its surface.

We used CNCJs program which has a macro name auto-level and what it does its make z probing along predefined distances and sort the values of the difference in the surface level and stores it so when the machine starts cutting he compensate this error.

Note:

There is other programs supporting this feature like candle software but we couldn't make it runs successfully.

Problems cannot be solved in the current time

These following problems cannot be solved in the meaning time because the shortage of time and lacking of knowledge required solving these problems.

1. Spindle speed control from the software

We currently doesn't know a way to control the spindle speed using the S code from the software so we replaced it by a manual PWM control with a potentiometer to control the speed of the spindle manually.

2. Cannot install hard limit switches

We tried to install the hard limit switches on the 2 sides in the X and Y axes and the top side on the Z axis but when the spindle begin to work in produces a lot amount of noise and affect the wires of the switches making the software falsely reads that the limit switches has been triggered.

3. Spindle noise while operating or cutting

Because of the spindle we use is a brushed type so it's produces a lot of noise when starts to work because the friction between the 2 brushes and the metal connector inside the spindle and the solution for this problem is to use brushless dc motor.

Safety add-ons for the machine:

1. Emergency Switch

It’s a latching switch which is used in case of emergencies to prevent any disaster from happening or accidents

2. Safety Acrylic Door

A transparent door which installed in the front of the machine to prevent any flying material to hit and hurt the operating person

3. Door Safety Switch

A switch installed beside the door which stops the machine movement and the spindle rotation in case of someone opens the door and resumes the motion or operation when the door is closed

Additions on the machine

These are some additions on the machine to makes it easier to use

1. Screw Knobs

A 3D printed parts installed at the end of X , Y screw to make it easy to rotate the screw manually to the desired location

Note:

The connection with the controller must be closed before rotating the screws manually

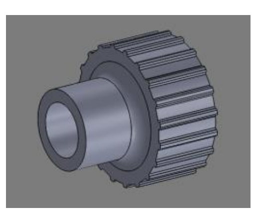


Figure 41 Screw Knob

2. **Attached laptop**

A laptop attached to the machine which has all the programs, files and soft-wares required to operate the machine without the need of someone's device

Further improvement (for other versions)

1. **Replacing the attached laptop with a raspberry bi and a touch screen**

2. **Install a better motor drivers prevent the sound coming from the motors**

How to operate the machine (machine manual)

Design-Upload-Run

These three words describe shortly the main stages to operate the machine and to get the desired product

1. CAD Stage

Here you design your product wither it is a 3D part or 2D part or even a PCB on a CAD program like SolidWorks, Inventor, and Proteus …..Etc.

After making your desired design you generate some files to proceed to the next stage, but here there is two paths depended on the product you design

For PCBs you need to generate Gerber files which are open ASCII vector format files that contain information on each physical board layer of your PCB design. Circuit board objects, like copper traces, vias, pads, solder mask and silkscreen images, are all represented by a flash or draw code, and defined by a series of vector coordinates. These files are used by PCB manufacturers to translate the details of your design into the physical properties of the PCB.

And also to generate Excellon drill format which is a file format used by drilling and routing machines from Excellon. It is a subset of RS274D, and is considered an industry standard.

For the 2D Files you need to generate a DXF files which are a Drawing Exchange Format file developed by Autodesk as a type of universal format for storing CAD models. The idea is that if the file format is supported in various 3D modeling programs, they can all import/export the same documents with ease

2. CAM Stage

In this stage you take the files you have been generated in the previous stage and upload it to a CAM program like Solid-Cam ,Art-Cam, Flat-Cam ,Powermill where you select the working parameters like feed rate in all axes and the depth of cut in case of 2D products

The output file from this stage is a gcode file which you need to proceed to the next stage

3. Uploading Stage

Here you take the NC file and upload it to a G-Code sender program which communicates with the grbl firmware which has been uploaded on the microcontroller board

Material and components price list

Name	Quantity	Total Price
Frame and Control box	---	1800
Stepper Motors	3	855
Arduino Uno	1	385
CNC Shield	1	115
Motor drivers	3	164
Spindle 500W with bracket	1	2000
PWM Controller	1	175
Power Supply 12V,240w	1	180
Power Supply 36V,500w	1	700
Linear rail	1.5 M	750
Linear guide	4	1000
Screw	1.2 M	250
Screw Nuts	3	96
Nut Block	2	126
Unti-Back lash Nut	1	70
AL Profile 2020	1	105
AL Profile 15180	1	185
Bearing Support	4	164
Soft Rod Support	4	164
Nuts & Bolts	1	150
Limit Switches	6	60
GX16 Connectors	13	234
Light	1	30
Cooling fan 220V	2	100
Waste board	1	30
Connections and wiring	1	200
Toggle switches	4	24
T nuts	33	100
Coupling	3	60
Silicon Spray Oil Lubricant	1	30
4040 Drop In nut	10	40
Chuck	1	178
Collet ER11	2	114
Test materials	1	500

Conclusion

From the various types of CNC machines we choose to make a 3 axes CNC PCB milling machine we started by collecting data about the products needed available in the local market and the prices in different places then we started to design the mechanical and electrical parts depending on the predefined specifications of the project and the available standard products that meet these specification then we assembled the machine with no design errors and then we started calibration and testing and the machine finally produced a high quality PCBs

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