UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

Laser Engraving and Milling CNC Machine: Design and Construction

Proyecto de Investigación

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Ingeniería Mecánica

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RESUMEN

Las máquinas de control numérico computarizado son esenciales dentro de la industria manufacturera. Las máquinas de fresado y grabado laser son usadas en la mayoría de las aplicaciones industriales a gran escala. En este artículo se detalla todo el proceso de diseño y construcción de una máquina de fresado y grabado láser, usando componentes de bajo costo y eficientes que aseguren un rendimiento preciso dentro de un ambiente semi industrial y para propósitos educativos. La máquina CNC construida fue probada con un módulo de fresado y un módulo laser. El módulo de fresado puede operar a 12000 RPM con una velocidad de avance máxima de 2500 mm/min. Por otro lado, el módulo laser tiene un desempeño optimo a una distancia focal de 38 mm y una velocidad de avance de 100 mm/min, restringida por la potencia de salida del láser. La máquina opera con buena repetibilidad bajo circunstancias normales y su máxima velocidad lineal de viaje es de 3000 mm/min gracias a la instalación de drivers TB6600 junto con motores Nema 17 y Nema 23. Después de varias pruebas es posible concluir que la maquina tiene una tolerancia de 0.6 mm para un proceso de fresado, mientras que la tolerancia en el proceso de laser es de 0.2 mm, ya que no se encuentran involucradas fuerzas de maquinado en el proceso ni vibraciones excesivas.

Palabras clave: diseño CNC, construcción CNC, laser, grabado, fresado, CNC multiherramienta, confiabilidad, precisión.

ABSTRACT

Computer Numerical Control machines are essential inside the manufacturing industry. Laser engraving and milling machines are usually expensive and are mostly used in large industry application. In this report, the entire design and manufacturing process of a laser engraving and milling machine is detailed using low cost yet efficient components to ensure a precise and efficient performance inside a semi industrial environment and for educational using purposes. The constructed CNC machine was tested with a milling module and a laser module. The milling module can perform at 12.000 RPM at a maximum feed rate of 2500 mm/min. On the other side the laser module optimal performance occurs at a focal length of 38 mm and a feed rate of 100 mm/min restricted by 1-watt power output of the laser. The machine performs with good repeatability under normal conditions, and its maximum linear velocity of 3000 mm/min is obtained thanks to the TB6600 drivers along with NEMA 17 and NEMA 23 stepper motors. After several tests, it is possible to conclude that the machine has a tolerance of 0.6 mm for the milling process, while the tolerance for the laser process is 0.2 mm because no working forces are involved in the process nor excessive vibrations.

Key words: CNC design, CNC construction, laser, engraving, milling, CNC multitool, reliability, accuracy.

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INTRODUCTION

In Ecuador the manufacturing sector has been constantly growing in last decade. One manufacturing technology that has grown in popularity is Computer Numerical Control (CNC) machines, which are useful for a variety of machining processes. Due to the complex design and powerful characteristics of these machines, the market price is usually very high. Even small CNC machines with basic configurations have prices oscillating around fifteen hundred dollars for the Piranha FX CNC up to four thousand dollars in the case of the Shark HD4 CNC. The high cost associated with these machines is due to their complex but efficient machining and software design (Hidayanti, Ambrizal, Farooqi, Alsultan, & Bin, 2017), which includes high speed stepper motors with powerful drivers, a robust design for heavy work, and a correct communication between the software and the hardware components. Because these machines are so expensive, their use is restricted for small businesses and educational bodies that cannot afford them.

CNC machines are industrial instruments that interpret commands containing numerical information and precisely execute them. This technology is ideal for automating manufacturing processes as they can be used in large variety of machining process such as cutting, engraving, drilling, welding, 3D printing, among others (Correa, Toombs, & Ferreira, 2017). In fact, most things that are used in everyday tasks were either partly or fully elaborated with CNC machine aid. Therefore, the main objective of this project is to develop a practical design of a budget friendly, easy to build, and highly precise laser cutting and engraving CNC machine. The machine will be designed and constructed following standard normative and utilizing components that can be easily found in Ecuador except for the transmission system and the laser module, which will be imported from the United States.

Along with the structural design and construction of the system, the electronic control of the machine is key to ensure a correct workflow. The machining flow of the system includes the CAD/CAM design, machining parameters of CNC controller, servo control, feed drive system and mechanical property (Chiu & Lee, 2017), as illustrated in Figure 1.

Computer-Aided Design (CAD) is formulated as G-code and interpreted into computer language to give control commands to the feed drive system that performs the actions required; this process is known as Computer Aid Manufacturing (CAM) (Hidayanti et al., 2017).

As a result of the industrial boom for manufacturing automation, incompatibility between controllers from different manufacturers has motivated the development of vendor neutral, open architecture controllers (OAC). Due to the low cost and high compatibility of open-electronics ecosystems with microprocessor-based platforms (Arduino, Ti LaunchPad, Teensy, Beaglebone), some NC applications like CNC routers, laser cutters and 3D printers have adopted open source hardware systems. An Arduino board running a Marlin firmware along with a Java Based Software will permit full control over the actuators and sensors of the system, as well as create an opportunity for easy automation of different manufacturing processes and custom-based CNC solutions (Correa et al., 2017). The design and development of the Software will not be part of the scope of this project, however, the main functions and the limitations of the software will be discussed, as well as the modifications needed to ensure a well operating machine.

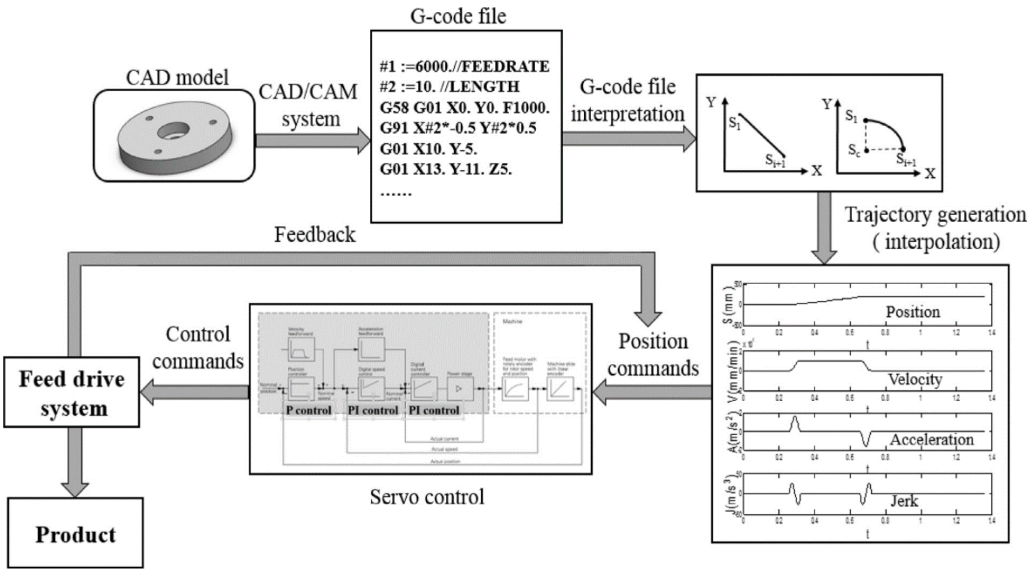

Figure 1: Illustration of CNC machining flow

Material processing using laser radiation is one of the fastest growing trends in the industry. It is possible to integrate devices that implement laser processing technology in the working area of the existing equipment (Ogin, Levashkin, & Yaresko, 2017). In this project the laser will be installed next to the milling router, thus the user will be able to perform either machining process without any hardware modifications and with minor software modifications.

The main problem for laser engraving machine control differs radically from the tasks of machines for traditional processing control like milling. For laser engraving, reaching the end of a NC block in the estimated time determined by laser frequency is obligatory (Martinov, Obuhov, Martinova, & Grigoriev, 2016). The impulse frequency within wide interval of 40 - 1000 Hz is used in the production area. For engraving in transparent environments, typically a low frequency is required. The interaction of the control system with the impulse machine during processing is shown in Figure 2.

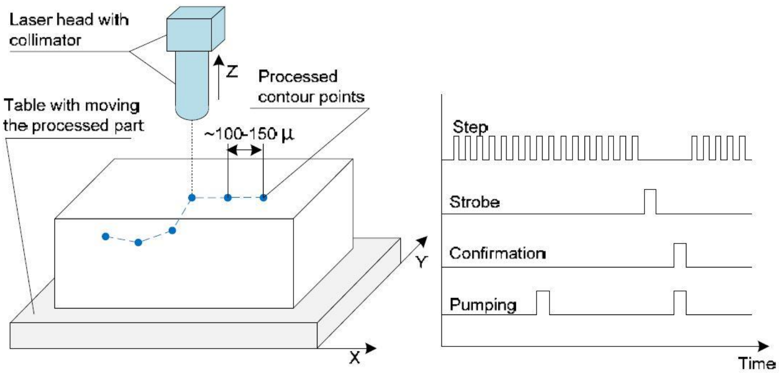

Figure 2: Scheme of interaction control system with pulsed laser machine

The material processing operation could be performed using continuous or in impulse mode depending on the application (Martinov et al., 2016). Laser technology provides advantages in cutting complex geometries and gives stable cutting quality which is required in most industrial processes. Laser energy can be applied directly on desired objects with easy control of its power and intensity. Laser engraving is the most effective technique in machining hard materials that have a complex geometry, being that the main reason why laser-based machining is widely used in many industries like mold making, automotive manufacturing, electronic parts and biomedical research.

In the manufacturing industry there are three most common types of lasers: fiber lasers, CO_2 lasers, and diode lasers.

Fiber lasers feature power options from 1 to over 100 kW, ideal or applications such as high-power cutting, precision cutting, welding, cladding and drilling. Fiber lasers have an end-to-end solid-state monolithic design without free space precision optics sensitive to alignment or contaminations (Photonics, 2018), aspects that make these lasers suitable for industrial working environments. Laser fiber prices range between $12.500 and $35.000 for 500W to 3000W options. These machines feature a water-cooling system, and are capable of a cutting thickness up to 25 mm at a maximum speed of 80 m/min.

CO_2 lasers present more affordable options, with prices ranging from $5.000 to $12.000 to 80W up to 150W options. These type of CNC machines have a water-cooling system and have a cutting speed of 48 m/min.

Finally, the use of diode lasers for material processing offers advantages that range from high energy efficiency, compactness, wavelength versatility, and low cost to high reliability. However, there is one important drawback with these systems, the poor beam quality sets a limitation in application field of these diodes. The agile development of laser technology from new researches found almost every month around the world, and recently advances in beam combining technology made it possible to scale the power of diode laser while maintaining an acceptable beam quality. It is important to consider 3 main aspects that affect the laser cutting and engraving process: the beam intensity and focus diameter, thermal interaction, and the beam-material interaction (Tönshoff et al., 1994).

In comparison with the CO_2 lasers cutters, the diode lasers have less power consumption but at the same time they have lower efficiency caused by the internal cooling of the system. Usually, diode lasers have a fan cooling system while CO_2 lasers have a water-cooling system

The frame will be designed and analyzed in Autodesk Inventor. The use of Computer Aid Design (CAD) allow us to calculate the characteristics and properties of all the materials used in the construction as well as the stepper motor torque required for a proper operation of the system. Many parts of the structure will be designed in Autodesk Inventor and 3D printed due to it complex geometry and some will be obtained and redesigned for our purposes from an online design community that gives free license to download their designs.

The proposed CNC machine includes linear x, y, z axis movement that will permit a precise and efficient machining process of different materials allowing students and teachers work jointly in the development of varied projects inside the USFQ Mechanical Engineer department. In order to guarantee a highly precise CNC system, a calibration, position accuracy and repeatability tests will be performed under different conditions and different environments. A vibration analysis of the system is very important to determine possible malfunctions of the machine and in order to perform a preventive maintenance.

METHODOLOGY

CNC DESIGN

The design of the CNC machine is divided into six sections: the sizing of the machine, the force analysis and the selection of the materials, the finite element simulation, the criteria to select the mechanical components, the criteria to select the electric and electronic components and finally the criteria to select the laser module.

Dimensions of the CNC machine.

The designing process starts with the definition of the characteristics and specifications of the machine. The working space area has been defined to 1.50 m in length and 1,30 m in width since most of standard materials that will be machined are flat sheets with approximate dimensions of 1.20 m x 1.20 m. The z-axis working distance will be limited to 20 cm—this distance allows a normal milling machining as well as laser cutting and engraving. In a milling machining process the perpendicular distance between the milling tool and the working piece is important because the tool needs a safe distance to move along the work surface without touching the working surface. In laser cutting and engraving processes, the distance between the working material and the laser module is used to focus the laser beam into the working piece.

Materials.

The frame of the CNC machine is constructed in A36 steel, a very common structural material that contributes to the robustness of the system, crucial factor in machines that experiences a lot of vibration and work forces. In the milling process, the working forces involved are the cutting force and friction force, therefore some vibration is involved in the process. On the other hand, for laser machining, there are no implied forces, which contributes no vibration to the system. As usual, the most critical and demanding operation is taking into consideration for the design.

The material selected for the porch is stainless steel, type C beams will support the weight of the machining tool and its components for its movement in the z axis. Additionally, the geometry of the beams contributes to the robustness of the system due to their resistance to bending.

The dollies are 3D printed in PLA and were designed to support the total weight of the moving structure and the machining forces. These components support the compression forces produced by the weight of the front portico and distributes this weight into 4 bearings located underneath each dolly. It should be noted that the 3D printed parts have a great performance when loaded to compression forces. This specific geometry permits the bearing to be located at a 45-degree angle, so they can slither through the rhomboid beam with almost no play.

The CNC machine has four main materials. The mechanical properties of these materials are listed in Table 1

Table 1. Mechanical properties of the CNC materials

Material	**Details**	**Young's Modulus (GPa)**	**Shear modulus (GPa)**	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**
A36 Steel	Frame material	200	145	250	400
Annealed AISI 302 Stainless Steel	Porch material	190	150	260	655
PLA	Dollies	1.28	1,287	70	73

Mechanical components.

Ball screws.

Ball screws offer advantages over roller screws and acme screws such as more precision, and more efficiency. Ball screws are very good in converting rotary motion into precision linear motion, these screws are also capable of move heavy loads, with great accuracy in a fast rate (Industries, n.d.).

To select the correct ball screw for the proposed CNC application, it's important to consider the desired load to move, desired speed, life expectancy, desired accuracy, and the dimension of the system.

The desired load to move is 90 N at an average speed of 3500 mm/min, the ball screw is expected to last at least 20.000 hours, which is the typical guideline for industrial machines. The required dimension of the ball screw is 1500 mm for the most critical part of the machine.

Considering the previously mentioned factors, the first step is to calculate the required Dynamic Rating Load, using the manufacturer catalog formula (SKF Catalog, 2013)

$$Ca = \left(\frac{60 \times L_h \times N}{10^6}\right)^{\frac{1}{3}} \times P_M \times f_w$$

This formula takes into consideration the desired life, rotational speed, applied load and a security factor for the application.

$$Ca = \left(\frac{60 \times 20000\ h \times 700\ RPM}{10^6}\right)^{\frac{1}{3}} \times 90 \times 2 = 1698.4\ N$$

Thus, the SFU 1605 ball screw is selected, a 16 mm diameter SFU series rolled ball screw with a single flange nut. This is a standard ball screw with low noise and adjustable seal system, ideal for normal automation applications (*Ball screws*, n.d.). The 16 mm diameter ball screw doesn't allow any deflection along the total length of the screw, aspect that is essential to avoid any extra forces and stresses, factors that can affect considerably the lifespan of the ball screw.

According to the manufacturer, the precision grade of this element is C7, which means that it has a travel distance error of 0.05 mm for every 300 mm. The precision of the ball screw is extremely important due to the expected precision of the CNC machine.

Table 2. Properties of precision ball screw.

Nominal diameter	**Lead**	**Basic dynamic load rating**	**Basic static load rating**	**Nut inertia**	**Screw mass**	**Screw inertia**
16 mm	5 mm	7.8 kN	10.7 kN	40 kgmm^2	1.95 kg	50.85 kgmm^2

As can be observed, the Basic Dynamic Load Rating of the selected ball screw is much higher than the required for the system. However, this ball screw had to be selected due to the dimensions of the system, and to avoid any bending of the screw.

Ball screw lap speed.

Before calculating the nominal life of the ball screw, the designer must determine the rotational speed of component.

The critical lap speed on the ball screw is dependent to the length of the screw and how it is fixed to the machine as shown in the Figure 3. Considering that the ball screw has one fixed, one simple end, and the total length of the ball screw is 1500 mm, the critical lap speed of the ball screw is 1500 RPM. The manufacturer recommends 80% or less of the critical speed as the normal rotation speed, which in the studied case, equal to 1200 RPM. It is very important to select 80% or less of the critical speed to avoid the screw's natural frequency attaining resonance, causing a lot of vibration in the system. Off course, this is not going to be the final speed of the ball screw, due to the torque limitations.

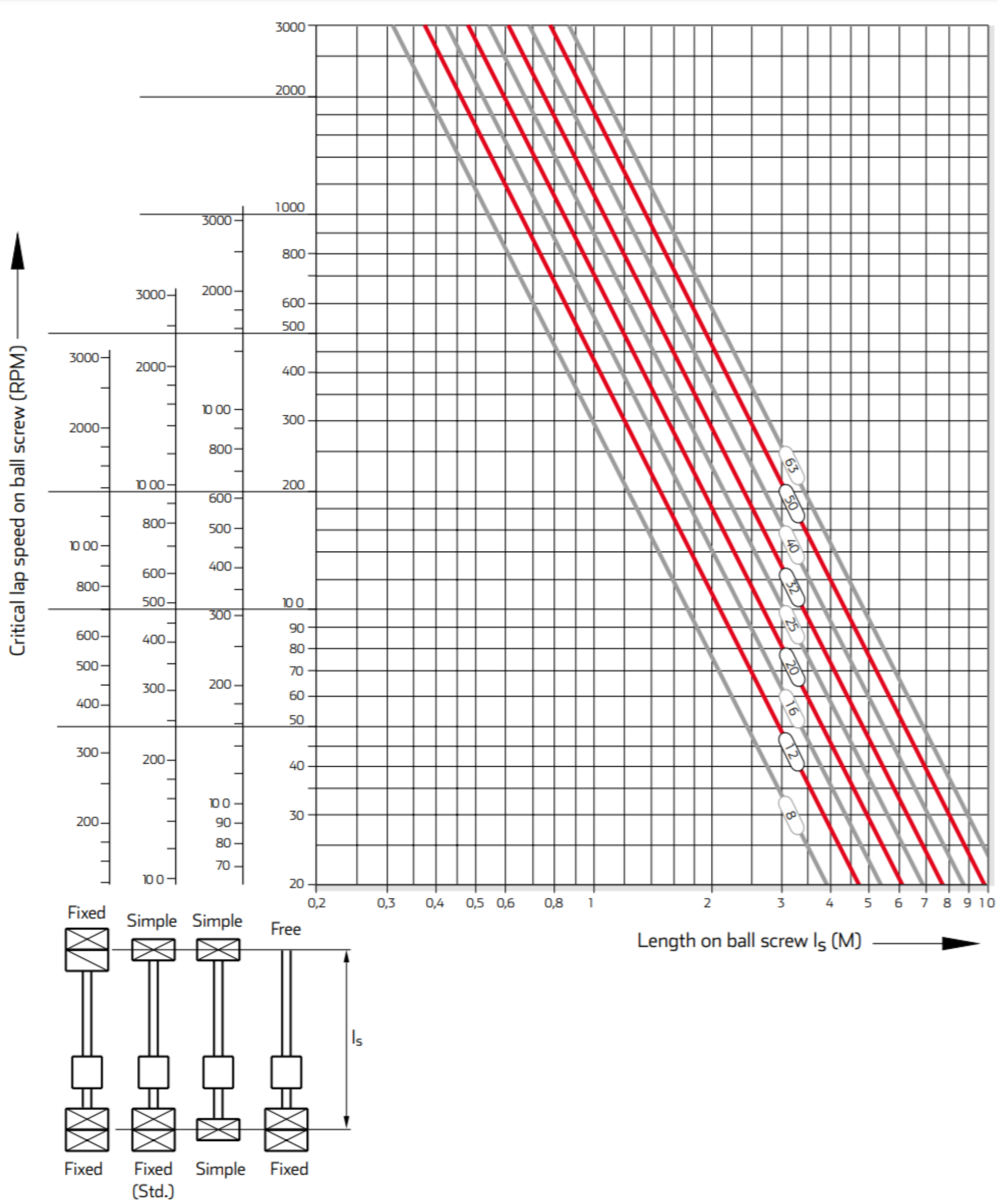

Figure 3. Ball screw critical lap speed.

For the z axis, the mounted of the ball screw will be modified due to the design of the dollies. In this case one side of the ball screw is fixed while the other side is free. The ball screw is 250 mm long, and as seen in Figure 3 it can rotate at a very high speed.

Torque

The system will use stepper motors along with power screws to move the laser and milling module through the whole work surface. The torque needed to produce a smooth and constant movement of the power screws is calculated considering the weight of the structure, the efficiency of the power screw, the inertia moment of the screw shaft, and the acceleration of the system. The next formulas are obtained from the product catalog (SKF Catalog, 2013).

Frictional torque by external load.

$$T_1 = \frac{Fa \times l}{2000 \times \pi \times 0.9}$$

The axial load in the ball screw is a combination of the process force and the mass moved multiplied by the coefficient friction of the sliding surface:

$$F_a = F + mgu$$

$$T_1 = \frac{90\,N \times 5\,mm}{2000 \times \pi \times 0.9} = 0.08\,Nm$$

Torque for preload.

The torque for preload (T_2) is not taken into consideration due to the horizontal configuration of the system.

Torque for acceleration.

$$T_3 = J \times \alpha$$

Where J includes the sum of the inertia moment of the motor (J_M), the ball screw (J_S) and the load (J_L):

$$J_M = 300\ gcm^2 = 3x10^{-5}\ kgm^2$$

$$J_S = 50.85\ kgmm^2 = 5.085x10^{-5}\ kgm^2$$

$$J_L = 5.55\ x10^{-4}\ \ kgm^2$$

$$T_3 = 0.000636\ kgm^2 \times 500\ {}^{rad}/_{s^2} = 0.318\ Nm$$

Torque during acceleration.

Usually, the torque during acceleration is the maximum required motor torque to move the load during the acceleration process. This torque takes into consideration the inertia of the system and the acceleration of the system.

$$T_{total} = T_1 + T_3 = 0.379\ Nm$$

606zz bearings.

The bearings were selected according the applied force and the movement requirements. Considering that the bearings will be loaded with axial and radial load, the 606zz bearings are selected. This specific type of bearings is perfect when working with heavy load and in high speed rates.

Deep groove ball bearing is suitable for high speed applications and can take radial load as well as some trust load, which is perfect for the application and the proposed design.

Bearing load.

In the machine, the bearings are used to ease the porch movement along the rail. Four bearings are in each dolly, oriented at a 45-degree angle to ensure full contact between the bearing surface and the rail.

The total weight of the moving structure will be equally distributed into the two superior dollies; therefore, each bearing will support one eight of the total weight. The load in the eight inferior bearings is small and for practical purposes is not going to be considered in the calculus.

Considering the orientation angle of each bearing, the radial and axial component of the force are obtained using the following procedure:

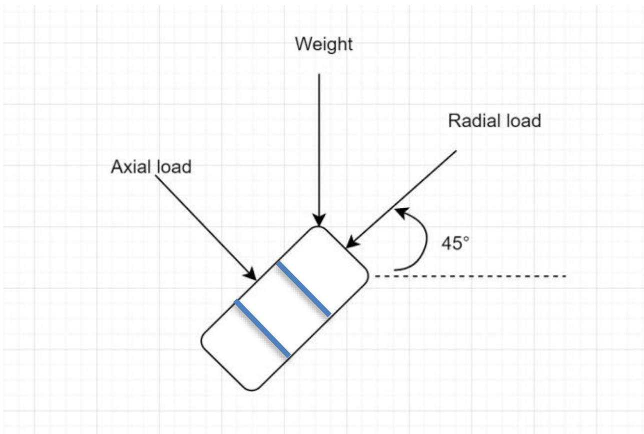

Figure 4. Bearing free body diagram.

$$F_{radial} = \frac{W/8}{sin\,(45)} = 31.82\ N$$

$$F_{axial} = \frac{W/8}{sin\,(45)} = 31.82\ N$$

The required life is 20000 hours, and considering the critical speed of the ball screw and the limitation of the stepper motors, the maximum linear velocity of the system is defined to 3500 mm/min. The following formulas are obtained from Shigley´s Mechanical Engineering Design.

Converting this to angular velocity, results in:

$$w = \frac{v}{r} = \frac{3500\ mm/min}{8\ mm} \times \frac{rev}{2\pi rad} = 69.63\ rpm$$

Relating the desired life with the rating life:

$$X_D = \frac{L_D}{L_R} = \frac{60 \times 20000h \times 69.63\ rpm}{10^6} = 84$$

When the bearing is loaded with radial and axial load, an equivalent load needs to be calculated:

$$F_e = \ X_i V F_R \times Y_i F_a$$

When the outer ring of the bearing moves V = 1.2. While X_i and Y_i are factors that depend of the construction and geometry of the bearing.

$$F_e = \ (0.56 \times 1.2 \times 31.82)\ + (1.89 \times 31.82) = \ 80.38\ N$$

A reliability of 0.99 is required, thus:

$$C_{10} = a_f F_D \left[\frac{X_D}{X_O + (\theta - X_O)(ln1/R_D)^{\frac{1}{b}}}\right]^{\frac{1}{a}}$$

Xo, $(\theta - X_O)$ and b are Weibull parameters. a_f is the application factor selected from Table 3.

Table 3. Bearing load application factor

Type of application	**Load factor**
Precision gearing	1.0 - 1.1
Commercial gearing	1.1 - 1.3
Applications with poor bearing seals	1.2
Machinery with no impact	1.0 - 1.2
Machinery with light impact	1.2 - 1.5
Machinery with moderate impact	1.5 - 3.0

$$C_{10} = 1.5 \times 80.38 \left[\frac{84}{0.02 + (4.439)(ln1/0.99)^{\frac{1}{1.483}}} \right]^{\frac{1}{3}} = 1945.4\ N$$

With the C_{10} specification, the 606zz bearing is selected.

The 606zz bearings have the next characteristics:

Table 4. 606zz bearings specifications.

Closure type	Double Shielded
Basic dynamic load rating (C)	1950 N
Basic static load rating (Co)	830 N
Fatigue load limit (Pu)	36 N
Maximum speed (grease)	35000 RPM
Maximum speed	42000 RPM

The 608zz bearings are sealed bearings, this type of bearings are lubricated at the factory, and therefore they are supposed to be lubricated for life. The user doesn't have to worry about the maintenance of this item until the lifetime of the same is achieved.

Force Analysis of the machine supports.

The CNC porch will be constructed using stainless steel C beams, rhomboid-shaped steel beams and 3D printed parts. The total weight of the moving structure is 180 N, weight that will be supported into two rhombus-shaped steel beams as shown in Figure 5. In order to determine the cross-section area of the beam, pure bending is considered along the beam. Considering that all the stresses and deformations occurs in the elastic range:

Maximum stress:

$$\sigma_m = \frac{Mc}{I}$$

Shear and moment analysis are performed in the software MDSolids, this analysis leads to a maximum shear stress of 45 N in the support points and a maximum moment of 33.75 N-m in the center of the beam. These results are shown in Figure 6.

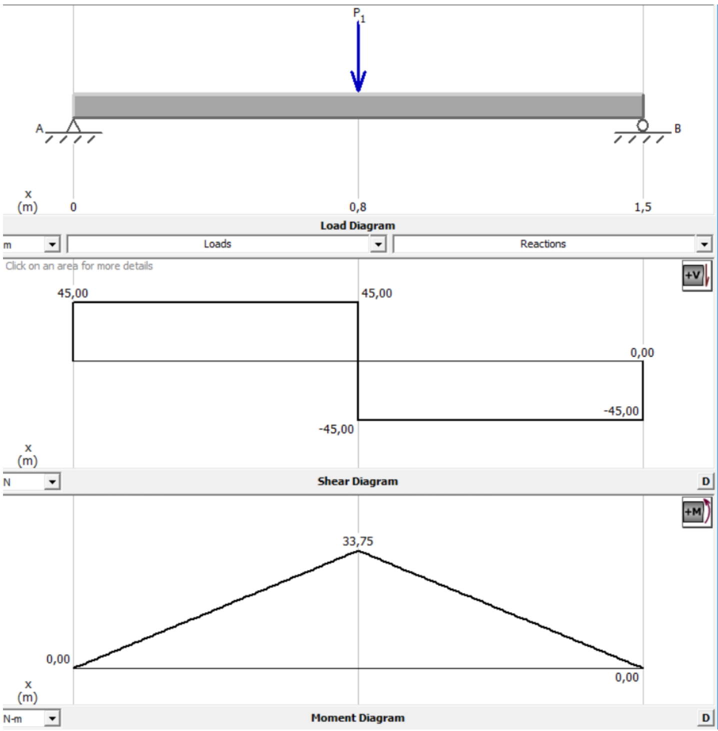

Figure 5. Shear and moment diagram of the lateral beams.

The geometry and the mounted position of the lateral's beams add more inertia and thus, the load applied to deform the beam has to be higher.

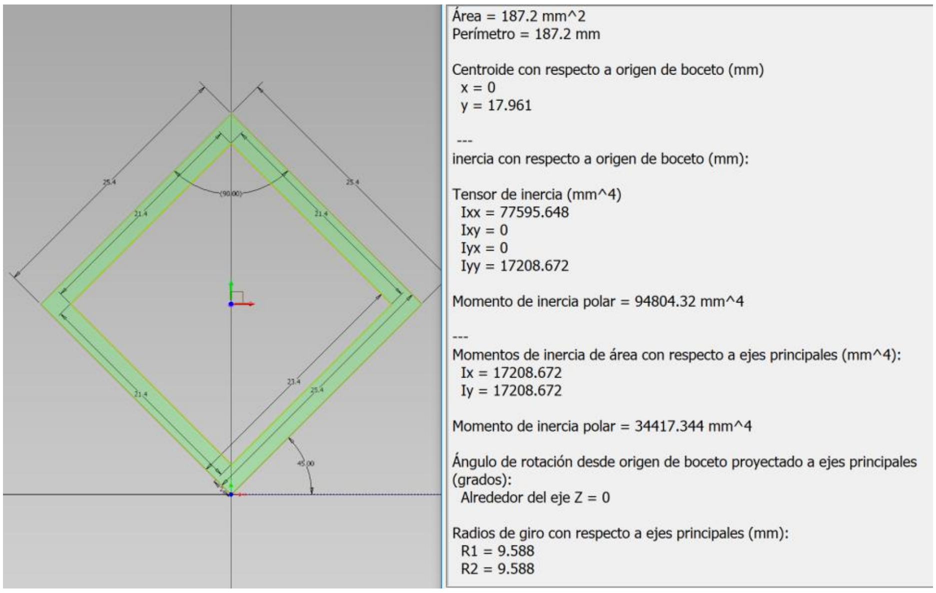

Figure 6. Properties of lateral beam.

Knowing the maximum moment created in the structure, the inertia moment and the largest distance from the neutral surface (c), it is possible to obtain the maximum stress in the beam:

$$\sigma_m = \frac{Mc}{I} = \frac{33.75\ Nm\ \times\ 0.0179m}{17208.67mm^4} = 35.22\ MPa$$

Safety factor

$$F.S = \frac{Yield\ stength}{Normal\ stress} = \frac{250\ MPa}{35.22\ MPa} = 7.097$$

A safety factor of 7.1 can be consider a very high factor and a possible indication that the system is oversized. However, due to the future improvements that can be done in the machine, such as the installation of a more powerful laser or a plasma cutter, the use of this type of square beam is correct.

Finite Elements Simulation.

The finite element simulation will be performed in the dollies that conform the portico, and in the machining tool to understand how the machining forces affect the structure that supports the tool and how the tool is affected by the processing. The first thing to considerate is the force that will be applied to the tool when milling. This can be calculated using the data from Table 5 ,and using the formula of power in milling process. The formula is the following:

$$U = \frac{F_c}{t_0 w}$$

Where U is the specific energy in Nm/mm^3 which can be obtained from Table 5 depending on the material of the stock. F_c is the Cutting Force, which is the force needed to obtain to use it on the simulation. t_0 is the feed (f), and w is the depth (d).

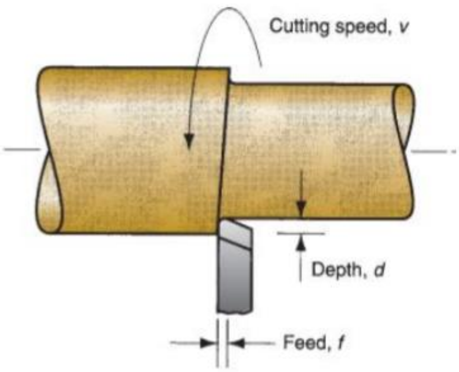

Figure 7. Machining conditions

Arranging the equation:

$$F_c = U t_0 w$$

Table 5. Specific Energy U from some metals

Material	Brinell Hardness	Specific Energy *U* or Unit Power P_u N-m/mm³	in-lb/in³	Unit Horsepower HP_u hp/(in³/min)
Carbon steel	150–200	1.6	240,000	0.6
	201–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
Alloy steels	200–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
	301–350	3.6	520,000	1.3
	351–400	4.4	640,000	1.6
Cast irons	125–175	1.1	160,000	0.4
	175–250	1.6	240,000	0.6
Stainless steel	150–250	2.8	400,000	1.0
Aluminum	50–100	0.7	100,000	0.25
Aluminum alloys	100–150	0.8	120,000	0.3
Brass	100–150	2.2	320,000	0.8
Bronze	100–150	2.2	320,000	0.8
Magnesium alloys	50–100	0.4	60,000	0.15

For the tests were made in wood, which has a lesser specific energy which means a lesser cutting force, the study conducted by Goli, G. et al give an idea of the cutting force Fc made on the tool. These tests were made with a 0.5 mm and 1.5 mm depth (w) and using different cutting angles (Goli, Marchal, Uzielli, & Negri, 2003).

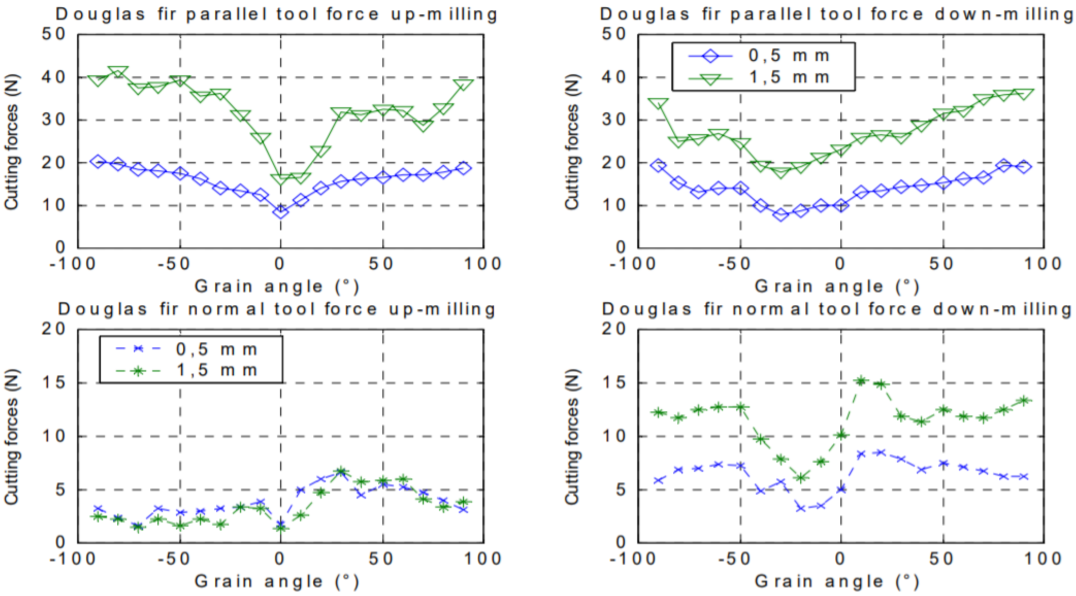

Figure 8. -90/90 diagram of cutting forces up- and down-milling Douglas fir with 0,5 and 1,5 mm of depth of cut (Goli. G, et al).

Assuming a force of 10N applied to the milling as shown in Figure 8.

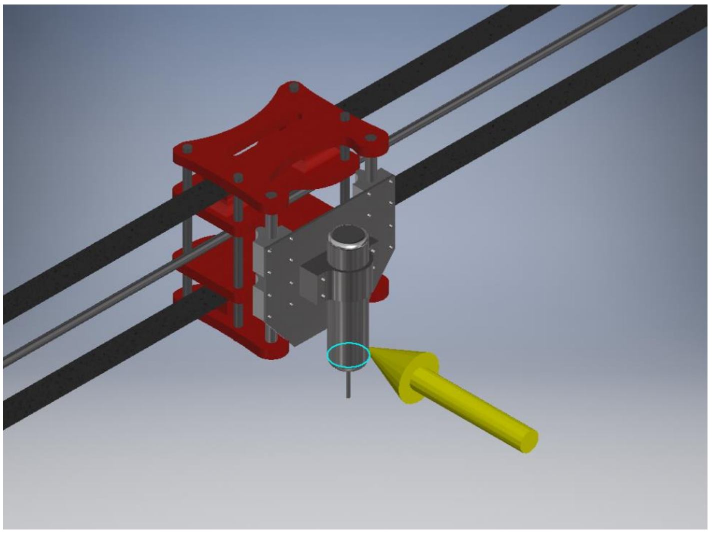

Figure 9. Force application in the structure using Autodesk Inventor.

With these parameters the Static Stress Analysis was performed on Autodesk Inventor.

Electric and Electronic Components.

The electric and electronic components of the machine need to be selected carefully to work perfectly with the mechanical components to produce a smooth and efficient workflow. In this section, the selection of the adequate stepper motors, drivers, controllers and other components is described.

Controller.

A microcontroller such as an Arduino is ideal for this type of application due to the open source software and libraries available and because it let the user control sensors and actuators.

The Arduino mega is the microcontroller used to send information via the ramps 1.4 mask to the stepper motors and laser diode, as well as receive information from the end stops. This microcontroller is connected to a computer to allow the user to upload the g code and perform changes in the main code.

Controller mask.

The RAMPS 1.4 is an Arduino Mega Shield module that allows an Arduino to control several parameters of a CNC machine. This mask allows the user to connect four stepper motors, three end stops for each axis in order to home the machine, one LCD module to operate the machine without having a computer, and a laser module.

Stepper motors.

Considering the calculated torque needed to move the structure and break the moment of inertia of the ball screw. Nema 17 and Nema 23 stepper motors are selected. The Nema 17 motors will be located to move the X and Z axis, while two Nema 23 will move the porch along the Y axis. The curve of torque of the Nema 23 motor shows that while the pull-out torque of the motor decrease, the working speed of the motor increases, this is the expected behavior in motors.

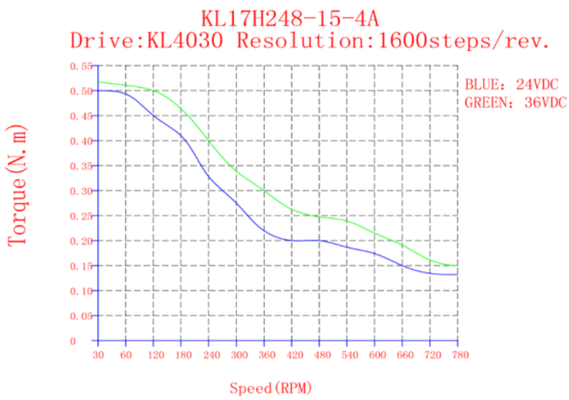

Figure 10. Torque and speed curve for Nema 17 stepper motors.

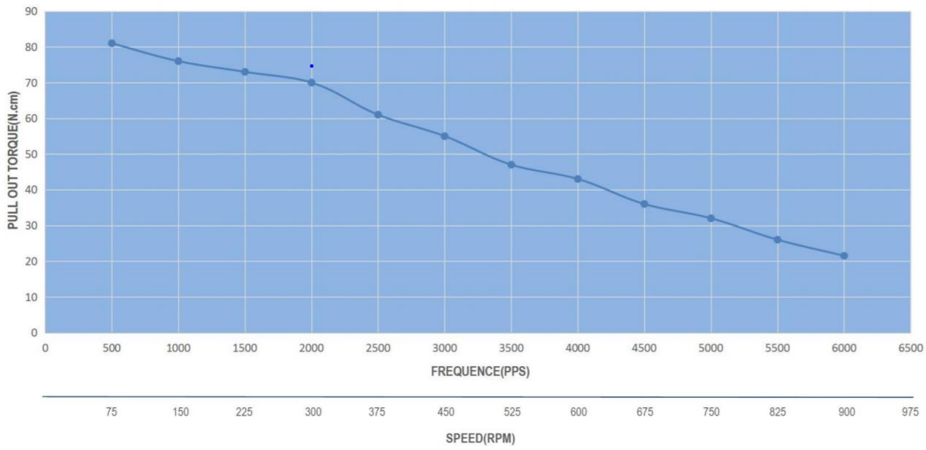

Figure 11. Pull out torque, frequency and speed curve for Nema 23 stepper motors.

Stepper motor Drivers.

The TB6600 based driver (HY-DIV268N-5A) is a two-phase hybrid stepper motor driver that supports speed and direction control. The driver has seven kind of micro steps and 8 kinds of current control, this allows a full control over the precision of the motor. The driver has a wide range power input, from 12V to 48V DC and also has 6 DIP switches to control the kind of micro steps (NC, 1, 1/2 , 1/2, 1/4, 1/8 , 1/16) and current control (0.2A, 0.6A, 1.2A, 1.8A, 2.5A, 3.3A, 4.2A, 5A) This driver will be used for both x and y axis.

The proper way to connect the stepper motor to the TB6600 driver, and to the Ramps board is shown in Figure 12.

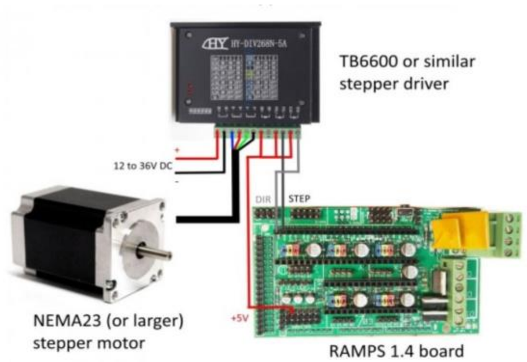

Figure 12. TB6600 Driver Wiring Diagram

End stops.

The use of end stops is crucial in the operation of the CNC machine because it allows a correct setting of the machine and a correct workflow. The main function of these sensors is to home the machine and limit the workspace. The end stops selected are inductive proximity sensors thus it can only detect metallic objects. The detection distance of this proximity sensor is 2 mm, this distance can vary with temperatures changes and/or supply voltage fluctuation. The normal detecting distance is 80% of the maximum operation distance.

The selected sensor has a normally open output (N.O.), meaning that the sensor will output an ON signal when a metallic object enters the detecting range.

The main characteristic as well as current and voltage consumption of the electronic components is described in Table 6.

Table 6. Properties of the electronic components

Component	**Main characteristic**	**Current consumption (A)**	**Voltage Consumption (V)**
Nema 17 Motor	Torque 0.44 Nm	1.5 - 1.8	4.0
Nema 23 Motor	Torque 1.26 Nm	2.8	2.5
Inductive Proximity Sensor E2EL-X2F1-M1	End stops	15 mA	5.0
Arduino Mega	Microcontroller	70 mA	7 -12
Ramps 1.4	CNC Mask	5	12 - 24
Driver TB6600	Driver for stepper motors Nema 23	0.0 - 5.0	12 - 36

The full diagram of the electronic components is shown in Figure 13.

Laser selection method.

A 1-W laser module can perform engraving in several materials such as wood, plywood, MDF, cardboard etc. The power output of the laser affects the engraving quality, and it is directly related to the focal length and the feed rate of the machining.

Table 7. 1-Watt laser diode specifications.

Characteristic	Description
Laser type	Nichia diode
Optical Power Output	1000 mW ± 15%
Laser Wavelength	445 nm
Voltage input	5 V DC
Current input	1-3 Amps

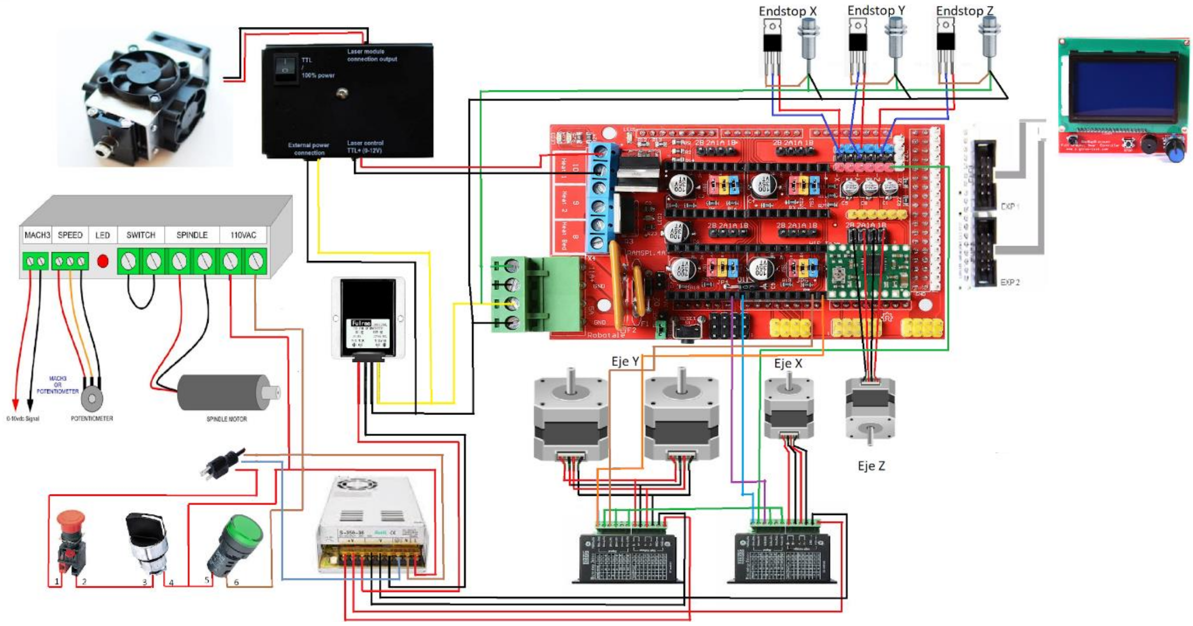

Figure 13. CNC machine wiring diagram.

CNC Firmware and Software

CNC machines use G-codes to move along the board and do the operations needed, but generating these codes is usually a draining task since the user needs a large list of codes for doing small crafts. With this concerning, developers have created many open-source CAM software's such as CAMotics, in which the user can simulate the toolpaths that the CNC will reproduce and hence have an accurate idea of what is going to happen, and the software delivers the G-codes necessaries to perform the machining. On the other hand, major developers have created software's like CATIA or Autodesk Inventor that are very expensive, but for academic usage Inventor is free and with the use of a plugin using its Application Programming Interface (API) for CNC or CAM simulation the end-users can manage to create and simulate CAM G-codes (Nair, Khokhawat, & Chittawadigi, 2018).

Software.

The process of design includes the parametric modeling which is the information regarding the geometry of the design and its dimensions that can vary across the design process. This process is accomplished with the aid of a computer software, where not only sketches are created but 3D models with features like Extrude, Revolve, Sweep, Fillet, etc., like Autodesk Inventor, CATIA, SolidWorks, etc. Once the CAD model is finished the end-user will start the CAM process, in which he will require to produce the G-Codes associated with his model in the software. The next step is having a firmware that can read and understand these G-Codes inside the main board of the CNC machine to perform the actions needed to complete the job.

Firmware.

The firmware utilized on a CNC machine have a lot of importance since all the G codes and commands will be processed in there and is where all the parts of the CNC will be integrated in one single functioning machine, as the firmware takes control of all the logic that controls the electronics of the machine at its lowest level. Although all CNC companies develop their own firmware for their use only, there are several numbers of free to use firmware's or clones that are very stable and friendly. One of these cases is the Marlin firmware which have been used for the development of the machine since it is for single-processor electronics, supporting RAMPS, RAMBo, Ultimaker, BQ, and several other Arduino-based machines, mostly 3D printers.

Firmware configuration.

For the first part of the design of the machine, which was a first approach for milling, the firmware was programmed to process information for Nema 17 motors using A4988 stepper drivers. Marlin is a friendly environment that can be easily programmed for different purposes and setups, although is made for 3D printing, this made us work with it. The modifications made are essentially selecting the type of electronics, the geometry of the CNC, the end stops configuration, and some extra features which needs to be modified from the Configuration.h archive.

First is selected a BAUD RATE of 115200, which is the communication speed of the CNC or the pulse rate in pulses per second. Next the motherboard is selected, since the board used in the project is an Arduino Mega with RAMPS 1.4 it is defined as:

MOTHERBOARD BOARD_RAMPS_14_EFB,

which is used for RAMPS 1.4 (Power outputs: Spindle, Controller Fan). The next step was configuring the end stops; for the machine used a Y min, an X min and a Z max which were defined as:

#define USE_XMIN_PLUG

#define USE_YMIN_PLUG

#define USE_ZMAX_PLUG

As for the configuration of the drivers you are using for your axis motors it is necessary to determine which one you are using. You can use drivers from the list (A4988, DRV8825, LV8729, L6470, TB6560, TB6600, TMC2100, TMC2130, TMC2130_STANDALONE, TMC2208, TMC2208_STANDALONE, TMC26X, TMC26X_STANDALONE, TMC2660, TMC2660_STANDALONE, TMC5130, TMC5130_STANDALONE), and are defined in the code as:

#define X_DRIVER_TYPE TB6600

#define Y_DRIVER_TYPE TB6600

#define Z_DRIVER_TYPE TB6600

Next comes the configuration of the default axis steps per unit (steps/mm). This varies with the characteristics of the ball screws and can be found on their data sheets. For our configuration where defined as { X, Y, Z, E0}:

#define DEFAULT_AXIS_STEPS_PER_UNIT   { 640, 640, 640, 500 }

For the default max feed rate, it needs to calculate the max speed at which the motors can operate without any trouble. After calculating this, it is defined in the code as { X, Y, Z, E0}:

#define DEFAULT_MAX_FEEDRATE { 2500, 2500, 2500, 25 }

The default max acceleration [(change/s) change = mm/s] is defined as { X, Y, Z, E0}:

#define DEFAULT_MAX_ACCELERATION { 800, 800, 800, 10000 }

And then the default acceleration is defined

#define DEFAULT_ACCELERATION 800 // X, Y, Z and E acceleration for printing moves

#define DEFAULT_RETRACT_ACCELERATION 1000 // E acceleration for retracts

#define DEFAULT_TRAVEL_ACCELERATION 800 // X, Y, Z acceleration for travel moves

The Jerk is a value that specifies the minimum speed change that requires acceleration. The Jerk is defined in the code as:

#define DEFAULT_XJERK 10.0

#define DEFAULT_YJERK 10.0

#define DEFAULT_ZJERK 0.4

#define DEFAULT_EJERK 5.0

The next step is configuring the end stops for each of the axis, having one end stop on the X axis, one in the Y axis, and one in the Z axis. Having the first two operating as min end stops and the last one mentioned as a max end stop. This is programmed in the code as:

// Direction of end stops when homing; 1=MAX, -1=MIN

// :[-1,1]

#define X_HOME_DIR -1

#define Y_HOME_DIR -1

#define Z_HOME_DIR -1

The bed size in the machine section is annotated:

// The size of the print bed

#define X_BED_SIZE 1000

#define Y_BED_SIZE 1250

Now, define the travel limits for the workspace and since the machine only have end stops at one side of each axis.

// Travel limits (mm) after homing, corresponding to end stop positions.

#define X_MIN_POS 0

#define Y_MIN_POS 0

#define Z_MIN_POS -70

#define X_MAX_POS X_BED_SIZE

#define Y_MAX_POS Y_BED_SIZE

#define Z_MAX_POS 0

Next, it is necessary to define the speed at which the machine will be homing as follows:

// Homing speeds (mm/m)

#define HOMING_FEEDRATE_XY (2500)

#define HOMING_FEEDRATE_Z (1500)

Finishing with the configuration of the firmware, proceed to compile and update to the Arduino board and begin to make some tests for the controllers and movement of the motors. In this stage it is expected that the board connects properly to the software with no errors.

Once the machine electronics and mechanics are working, calibration is necessary to ensure proper functioning and well finished milling or laser cuts and engravings.

LASER EQUIPMENT MOUNTING AND TESTING

The proposed 1 watt laser is to be mounted in the same z plate where the milling router is held, this provides the opportunity of having both tools ready to perform. This will not alternate or interfere with the milling performance since the laser occupy a small place beside it and does not create any forces that affect the stability of the portico.

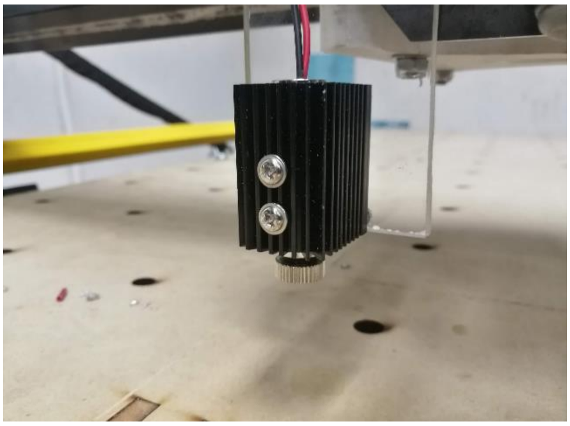

Figure 14. Laser equipment mounting.

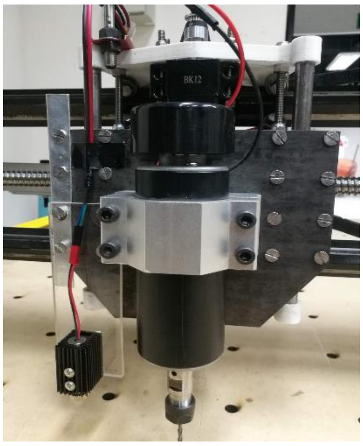

Figure 15. Laser equipment mounting.

The wiring of the laser module is as described in section 2.1.6, operating on the D9 pin of the ramps 1.4 which has an output of 12 volts. This allows the Marlin firmware to control it with the commands M106 S255 for turning the laser on and M106 S0 or M107 to turn it off. The firmware code does not need to be modified but to be sure the D9 pin is working, the user can enable the pin in the code by defining properly the *MOTHERBOARD* as of *RAMPS_14_EFB* as described in section 3.

Using the software *Inkscape* along with *Laser Jet G code generator plug-in*, it is possible to create g-codes for cutting and engraving with the laser, this software allows the user to configure the laser power output, machining speed, travel speed, number of required pass, and the down step for each pass.

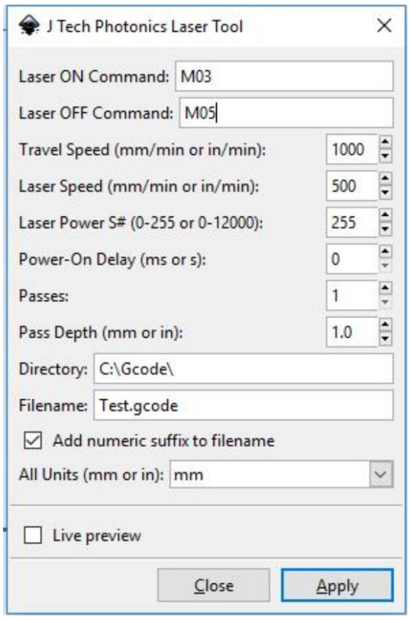

Figure 16. J Tech Photonics Laser Tool Extension

Optimal engraving focal distance.

The focal distance of the laser beam is fundamental in a good machining process, a correct distance assure that the laser can make a clear engraving path. To measure the optimal focal lens distance, paths were engraved from 45 mm to 33 mm of distance between the laser module and the workpiece as shown in Figure 23

Optimal engraving feed rate

The second test consisted in experimentally finding the best machining velocity or feed rate where the laser is capable of perform a good quality machining. This test consisted in create different toolpaths with a fixed z distance (38 mm), as shown in Figure 24, varying the feed rate of the machine, this allowed to see how the engraving paths changed with each feed rate.

SYSTEM CALIBRATION

Once the machine is built, make sure all the nuts and bolts are properly tightened down and make sure the machine is on a flat and leveled surface.

Once the physical building process for the machine is finished, calibration is needed to obtain good quality machining results. Without a proper calibration, machined pieces may not have the correct dimensions or other defects may occur. It is important to mention that calibration is an ongoing process that needs to be performed once every while throughout the life of the CNC machine, so the machining processes keep the quality.

The first thing to calibrate is the stepper motors by setting the optimal current level. Motors should run quietly or occasionally make some sounds, but a fair amount of noise means a problem. If the motor vibrates without turning, means current is insufficient or the steps/mm are way incorrect. If motors make significant noise or movement on the axis pauses momentarily, means the current is overloaded. The motors were calibrated adjusting the current provided by the drivers down until motors vibrates without movement of the axis and start elevating the current until the motors start running, then give a little extra current and motors are calibrated.

Then to assure the machine is moving correctly, different paths and movements were performed in the 3 axes to obtain the travel distances and compare them to the distances that the machine was commanded to move. If there are discrepancies between these dimensions, it could mean rather the motors are misconfigured or there are mechanical problems in the ball screws or related movement components.

To ensure a correct level of the machine, the z distance was measure in 9 points along the workspace, correcting the distance when necessary with the bolts located at 9 positions in the workspace.

MILLING AND LASER TESTS

The laser and milling test were performed to determine the tolerance and precision of the machine. Several geometric figures were created using AutoCAD and the machining using the milling module, and then the laser module. This test allows the user to compare the results and discuss the presented variations.

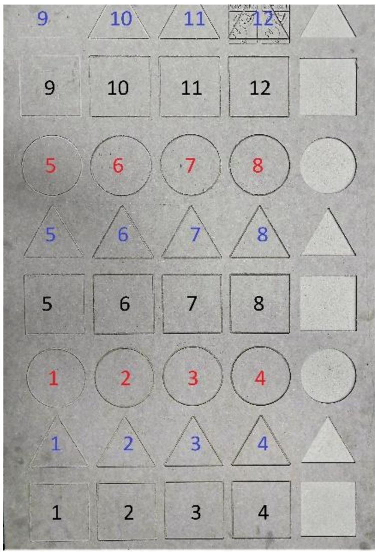

Figure 17. Milling and laser tests diagram

VIBRATION MEASUREMENT

The vibration analysis is important in the current project. The milling process generates noise and vibration in the system due to the high-speed angular velocity of the milling router and the contact forces between the tool and the workpiece. This vibration in conjunction with the vibration produced by the rotary motion of the ball screws can affect the final product and the expected tolerances.

The objective of the vibration measurement is to determine how the milling process differ from the laser process. The principal difference between these two processes is the angular velocity of the milling module as well as the contact forces involved in the process.

The vibration measurement is done in all axes. The X axis has presented more vibration than the other two, due to the mounting in the machine. The vibration measurement will be divided into two experiments, each experiment with three sections. The feed rate of the machine, as well as the machining process will be the two key aspects of the experiments.

Experiment one

The first experiment will be performed without contact forces and with the laser module turned OFF. This will replicate a normal machining process using the laser module, and the objective is to determine the optimal machining velocity to avoid any imperfection in the final product. The results of this experiment are shown in Figure 32, and Figure 33.

Experiment two

The second experiment is performed using the milling module and the spindle tuned ON at 12000 RPM. The experiment replicates a normal milling machining at different feed rates. The results are shown in Figure 29, Figure 30, and Figure 31.

RESULTS AND DISCUSSION

The final version of the CNC machine is presented in Figure 18, and Figure 19. This machine includes all the elements and components, and. Additionally, all the tests previously mentioned have been performed. This CNC machine is capable of laser and milling processes with good precision. The machine is now fully operable with a 1250x1000 bed size and a top speed for the motors and ball screw power transmission of 2500 mm/min which is the top speed configured in the firmware. with a linear top speed of 3000 mm/min for travel and non-machining movements.

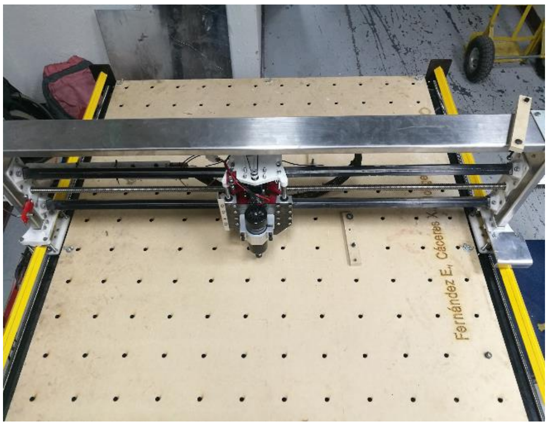

Figure 18. Fully assembled CNC machine, upper view

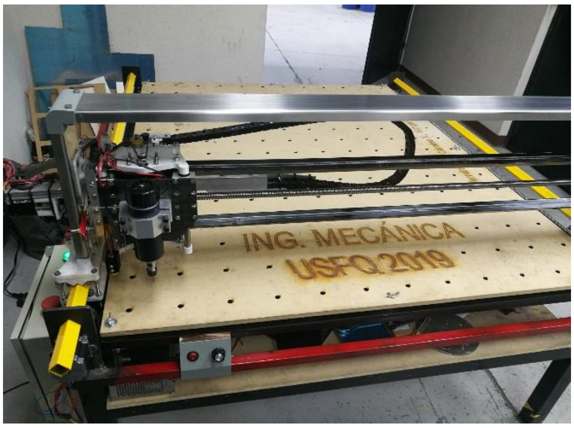

Figure 19. Fully assembled CNC machine, front view

The results obtained in the Finite Elements simulation are tabulated in Table 8.

Table 8. Simulation results summary

Name	Minimum	Maximum
Von Mises Stress	0 MPa	
1st Principal Stress	-1.34395 MPa	
3rd Principal Stress	-2.93163 MPa	1.54746 MPa
Displacement	0 mm	1.6171 MPa
Safety Factor	15 ul	0.455868 MPa
X Displacement	-0.0010526 mm	0.52837 MPa
Y Displacement	-0.00602282 mm	1.00858 MPa
Z Displacement	-0.0294986 mm	0.00101573 mm

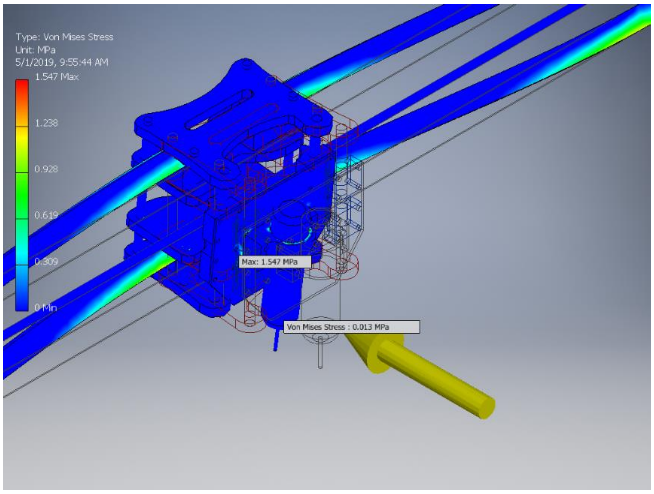

Figure 20. Von Mises Stress of the frontal structure.

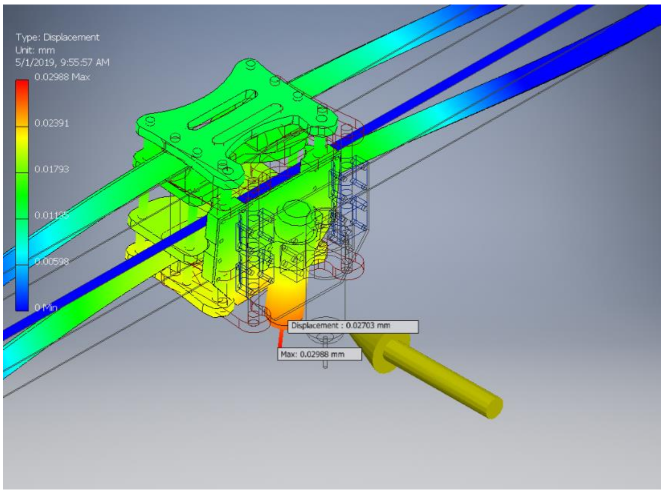

Figure 21. Displacement of the frontal structure.

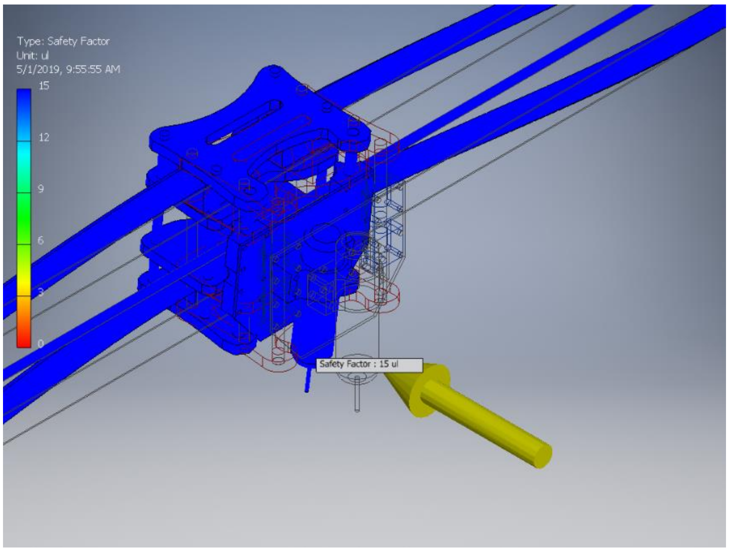

Figure 22. Safety Factor.

With the finite element analysis results, the machine setup for the portico is robust enough to perform on wood, acrylics and other soft materials. The data collected on the summary on Table 8 brings a maximum Von Mises Stress of 1.55 MPa, and a total displacement of 0.03 mm, which is a satisfying tolerance for the processes that the machine will carry. Also, the analysis shows a safety factor of 15 in the portico structure for wood processes.

The results obtained at different focal distances are the following:

Figure 23. Engraving paths at different focal distance.

After performing the optimal focal distance test, the engravings detailed on Figure 23 have been compared and from visual inspection is determined that the best focal distance ranges between 36 mm and 40 mm.

The results obtained at different feed rates are the following:

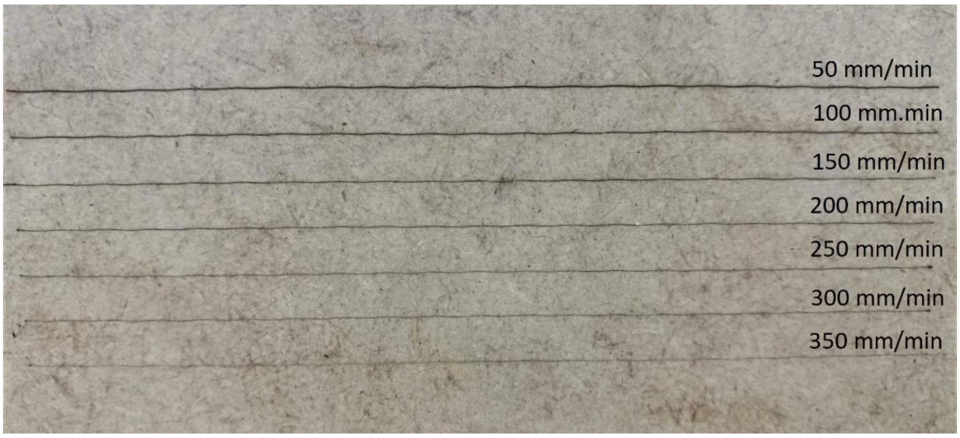

Figure 24. Engraving paths at different feed rates.

As shown in Figure 24, a good engraving path can be obtained from 50 mm/min to 150 mm/min. It's worth emphasizing that the optimal engraving velocity of the 1-watt laser is directly correlated with the output power of the instrument. More powerful laser could perform at higher feed rates without compromising the quality of the machining. The performed engraving, with visual inspection, shows a variation in the smoothness of the line that can be associated with vibrations produced in the portico. These vibrations are analyzed with a vibration analysis with the following results.

The precision of the engraving figures oscillates between 100.00 and 100.6 mm. This indicates a tolerance of 0.6 mm for the square shape figures.

An improvement that must be carried out to the machine to reduce the vibration is replacing the rails and using a stronger motor holder since the vibration is produced by the motor and the movement of the portico dolly.

Results for precision tests:

Milling precision test

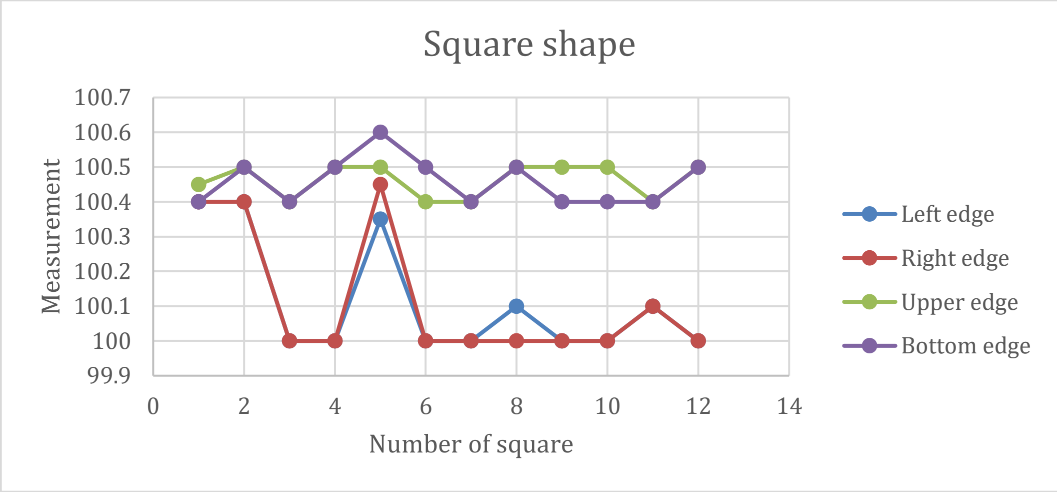

Figure 25. Square shape measurements

The precision of the engraving figures oscillates between 100.00 and 100.6 mm. This indicates a tolerance of 0.6 mm for the square shape figures. As shown in the figure the measurements for the left and right edge are very similar, as well as the measurements for the upper and bottom edge. However, the measurements vary 0.4 mm approximately when measure another axis.

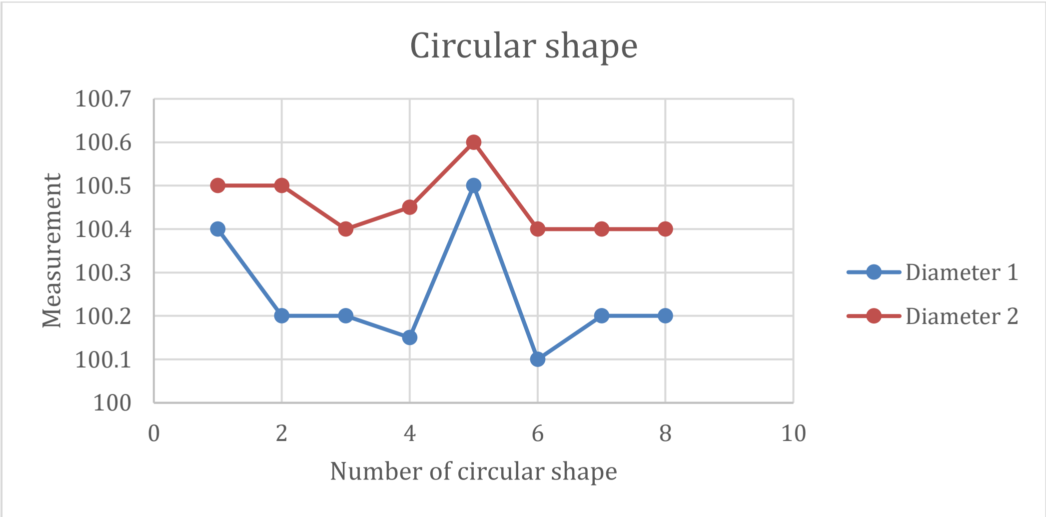

Figure 26. Circular shape measurements.

As can be seen in Figure 26, the diameter measurements vary from 100.1 to 100.6 mm. This indicates a tolerance of 0.6 mm. Analyzing the obtained data, it is possible to observe that the measure for the horizontal diameter vary from the vertical diameter, this is a strong indication of a wheelbase between axes.

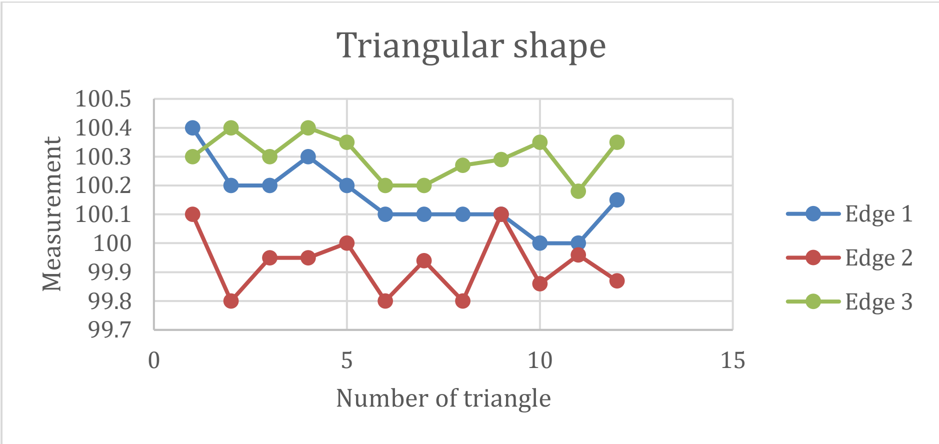

Figure 27. Triangular shape measurements.

The last test performed aimed to compare the milling process with the laser process, this test showed that the milling process present more error due to the machining forces and the feed rate of the tool. On the other hand, the laser process is more precise, with a tolerance of 0.2 mm.

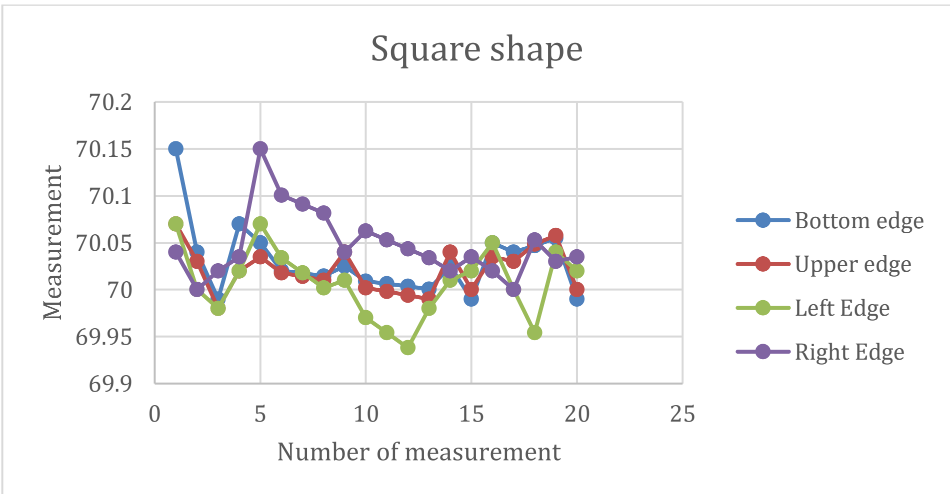

Figure 28. Results for laser machining.

The results presented in Figure 28 shows that the tolerance for the laser machining is lower than the tolerance for milling machining. This phenomenon is produced because the laser process do not experiment any machining forces nor vibrations.

Results for vibration tests:

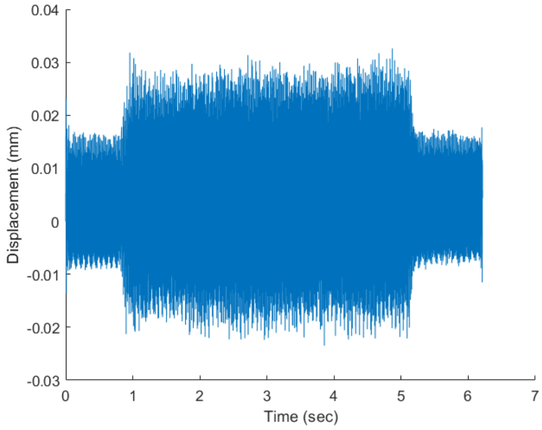

Figure 29. Vibration measurement in x axis while machining.

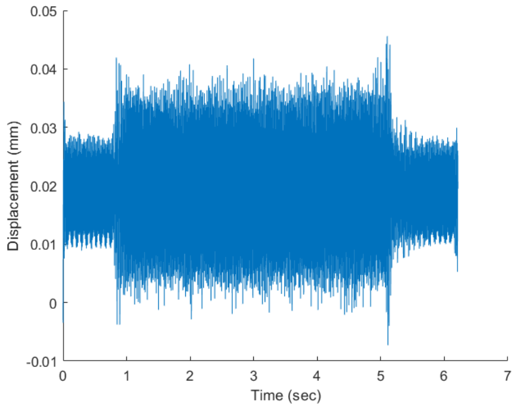

Figure 30. Vibration measurement in y axis while machining.

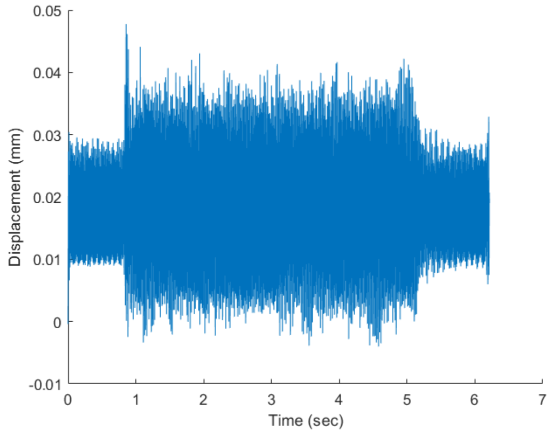

Figure 31.Vibration measurement in z axis while machining.

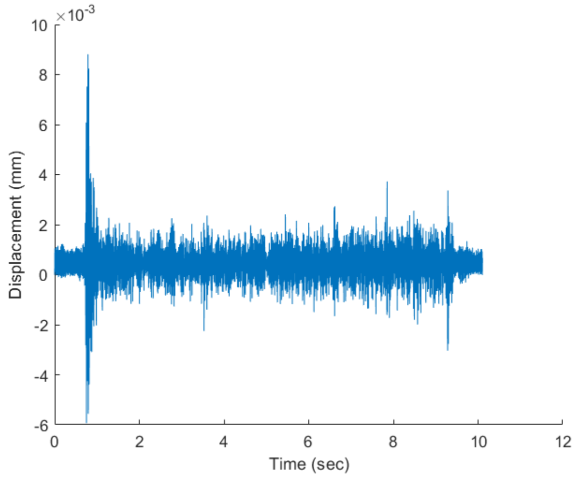

Figure 32. Vibration measurement in x axis.

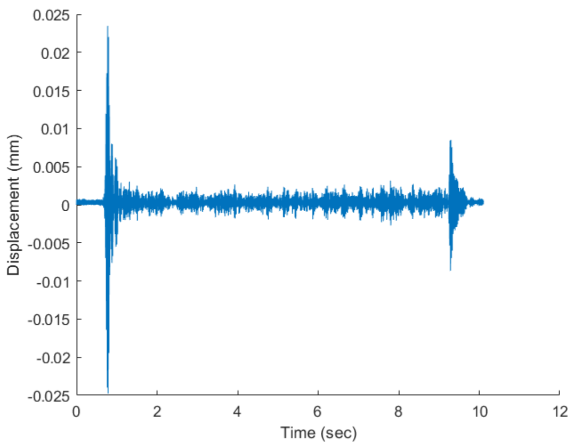

Figure 33.Vibration measurement in y axis.

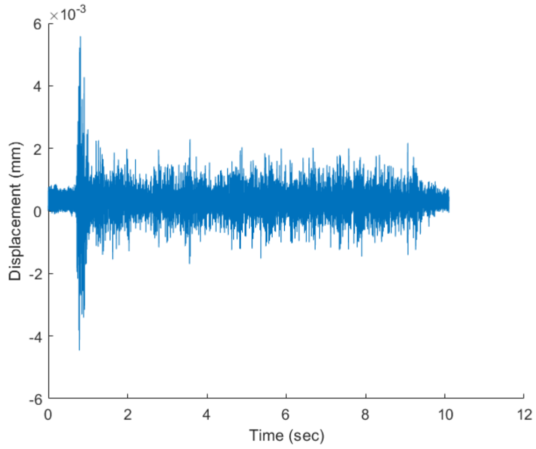

Figure 34. Vibration measurement in z axis.

As it is shown in the figures 29 through 33, the vibration is proportional in all axis while machining, but when the machine is not machining the vibration is stronger y the y axis direction. This information is helpful for determining some problems that the portico of the machine has and is a first step in a vibration analysis that can help to find eccentrics problems or misalignments.

CONCLUSIONS

The design and construction of the CNC machine was satisfactory, and it fulfills all the client requirements including the multitool performing which means the machine can perform with two modules, a milling module and a laser module. All the mechanical components were properly selected meeting all the design requirements. The acceleration of the system was determined experimentally, and the optimal performance was found in a range of 500 to 1500 mm/s^2. Similarly, the linear velocity of 3000 mm/min was found to be the maximum velocity for smooth travel movements without system failure.

After all the tests and experiments performed with the machine, the results showed that the machine have a machining tolerance of ±0.6 mm for a milling process. This tolerance is affected by the machining forces, the angular velocity of the spindle and the linear velocity of the system.

For the laser process, the optimal focal length ranges between 36 and 40 mm, while the optimal feed rate ranges between 50 and 150 mm/s. In the test performed with the laser module it is possible to conclude a tolerance of ±0.2 mm, significantly lower than the milling process. The lower tolerance occurs because no machining forces nor vibrations are presented in the process.

From the finite element simulation, the data throws that the portico is designed under a safety factor of 15 for wood machining. The analysis was made for the portico since it is there where all the stresses affects the smoothness of the movements, critically on the X axis. The major displacement is found on the tool, having a displacement of 0.029 mm, and a Von Mises Stress, which is a magnitude referred to the distortion energy and the theories of failure, of 1.55 MPa which together with the maximum displacement gives the safety factor of 15. Also, while performing milling, the vibration analysis shows that this is true since the displacement and vibration caused by the machining are not over the tolerances discussed in the literature. Although there must be changes in the portico since the laser engraving results shows lines with a slight wave form, the results of the precision analysis show that the tolerance is small enough for a precise milling.

The vibration analysis showed that most critical vibrations occurred in the z axis while performing milling, while for a laser process the vibrations are less significant. Additionally, the vibration of the system increases when the linear travel speed increases. This vibration analysis is a good start point for a maintenance process, where the user can compare how the vibrations change over the time and predict possible failure.

A previous work presented by Esteban Fernandez used Nema 17 motors with drivers A4988 and a milling module of 80-W, performing at a maximum linear speed of 400 mm/min without failure (Fernández, 2018). With the upgrades given to the machine now it is possible to have both a laser and milling processes, using a 500-W milling module and a 1-W laser. The laser module can be upgraded without changing the machine structure and configuration. Also, the travel speed was increased to more than 5 times and with better tolerances, from ±1.5 mm to ±0.6 mm.

It is important to mention that the machine is not able to cut with the installed 1-W laser module, caused by the power output of the instrument. However, if a more powerful laser module is installed, the machine has the firmware and hardware configuration to perform efficiently and with good precision.

As recommendations for future work, it is needed to change the 3D printed pieces for rigid ones which can be made of steel or aluminum. From the vibration measurement the portico shows some vibrations that can be caused by the momentum created with the x ball screw end which ends on a cantilever, this should be machined and cut to a proper size. Also, the laser diode should be replaced for a more powerful one which can be a CO_2 laser or a fiber laser.

The working area should be rigidized to make the machine capable of machining harder materials as aluminum.

Finally, a proper maintenance of the machine is crucial for a good performance, it is recommended a periodical 6-month maintenance, which includes: cleaning all the screws and the workspace, degrease all the components and perform a proper lubrication and calibration. Also, it is necessary to calibrate the system before any machining process to ensure a perfect performance and to avoid any malfunction.

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APPENDIX A: USER MANUAL

1. **Clear the workspace.** Make sure that the workspace is clear and that the machine can move freely in all directions. ***Caution****: The presence of any object in the workspace can cause misalignment due to impact*

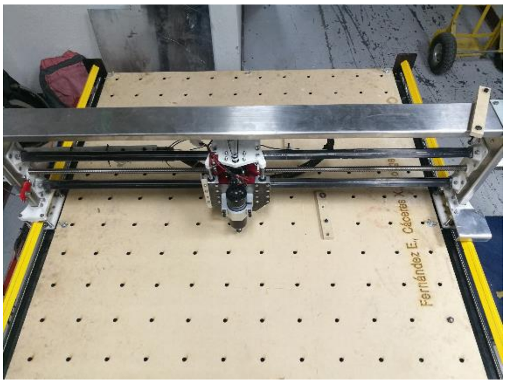


Figure 35. Workspace ready for machining.

2. **Turn ON** the CNC machine

Figure 36. CNC control box.

3. Take the machine to the origin.

3.1. **Homing using the LCD module:** When using the LCD module, homing the machine can be done accessing to the Main Menu → Preparar → Llevar al origen.

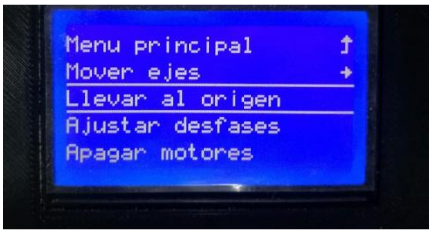


Figure 37. LCD menu for homing the machine

3.2. **Homing using a computer.** Connect your computer to the machine via USB and open a CNC software. Pronterface allows the user homing the machine with a simple click in the home icon.

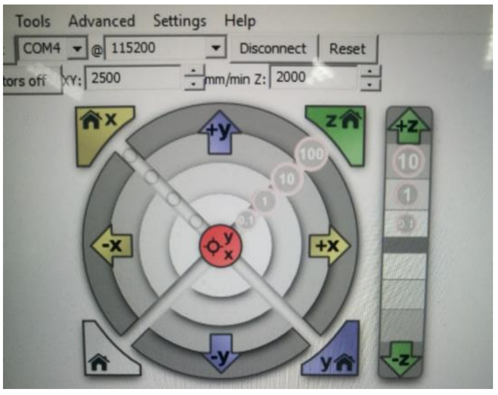


Figure 38. Pronterface interface.

4. Place and secure the workpiece into the workspace using the provided holders.

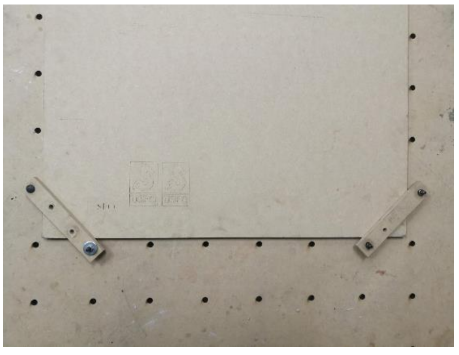


Figure 39. Workpiece secured into workspace.

5. Select the desired machining module. The milling spindle module as well as the laser module are pre-installed in the machine and can be used in any time. It is not necessary to plug or unplug any connectors. However, for each module it is necessary to follow the next instructions:

MILLING MACHINING

- Place and secure the adequate milling bit for the operation

Figure 40. Milling bit close up.

- Place the tool in the inferior left corner of the workpiece, with the milling tool touching the working piece, and use the command G92 X0 Y0 Z0 to indicate the zero piece to the software.
- Turn ON the milling module using the red switch located in the front face of the machine. Adjust the spindle RPM according the desired worked material. Figure 41 presents the formulas to calculate the feed rate, cutting speed and other parameter of machining.

Cutting Speed	$Vc = \frac{\pi \times D \times n}{1,000}$
Spindle Speed	$n = Vc \div \pi \div D \times 1,000$
Feed	$Vf = n \times fz \times Z$
Feed per Tooth	$fz = \frac{Vf}{n \times Z}$

Vc =	Cutting Speed (m/min)
π =	3.14 [The Circular Constant]
D =	Diameter (mm)
n =	Spindle Speed (min^{-1})
Vf =	Feed (mm/min)
fz =	Feed per Tooth (mm/tooth)
Z =	Number of Flutes

Figure 41. Machining parameters

Figure 42. Spindle control board.

- Import the desired g-code.
- Run the g-code and supervise the machining process in case of malfunction.
- Enjoy the final product

LASER MACHINING

- Generate the Gcode using the software Inkscape along with the J tech Photonics laser plug in, as shown in Figure 43.

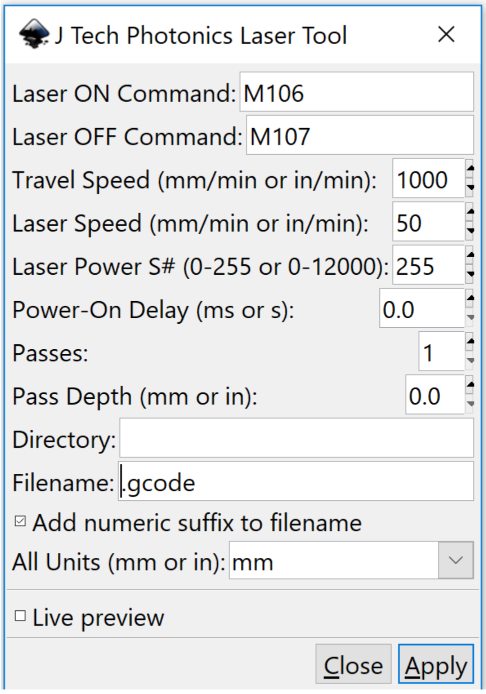


Figure 43. J Tehc Photonics plug in.

- Place the laser in the bottom left corner of the working machine at adjust the focal length. The 1w laser module focal length ranges between 36 and 40 mm.
- Once the focal distance is set, write the command G92 X0 Y0 Z0 to indicate the ero piece to the software.
- Upload the g code.
- Run the G CODE.

APPENDIX B: MAINTENANCE MANUAL

BALL SCREW LUBRICATION

Taking into consideration the load applied to the ball screw, the rotation speed and the environmental working temperature, it is recommended to lubricate the ball screw transmission system every 1000 working hours or every six months.

Temperature	10-40º C	
Rotation speed	**under 600 rpm**	**over 600 rpm**
Ball screw size	**Load**	**Load**
8, 10, 12, 15 and 16	up to 15 kg	over 15 kg
20	up to 60 kg	over 60 kg
25 and 32	up to 100 kg	over 100 kg
40 and 50	up to 250 kg	over 250 kg
63	up to 400 kg	over 400 kg
Lubrication interval every	1000 hours	750 hours

Figure 44. Lubrication intervals for ball screw.

It is important to use the right amount of lubricant to avoid any problems. For the 16 mm ball screw, it is recommended to use 4 grams of lubricant. The lubrication process needs to be done through the grease holes in the ball nut. It is important to use ball bearing grease and make sure that the lubricant does not contain graphite or molybdenum disulphide, this chemical can affect the correct operation of the ball screw.

Size	Amount of lubricant
8, 10, 12, 15 and 16	4 gm
20	7 gm
25	9 gm
32	13 gm
40	16 gm
50	19 gm
63	25 gm

Figure 45. Amount of lubricant for different ball screw size.

Mechanical Components Replacement.

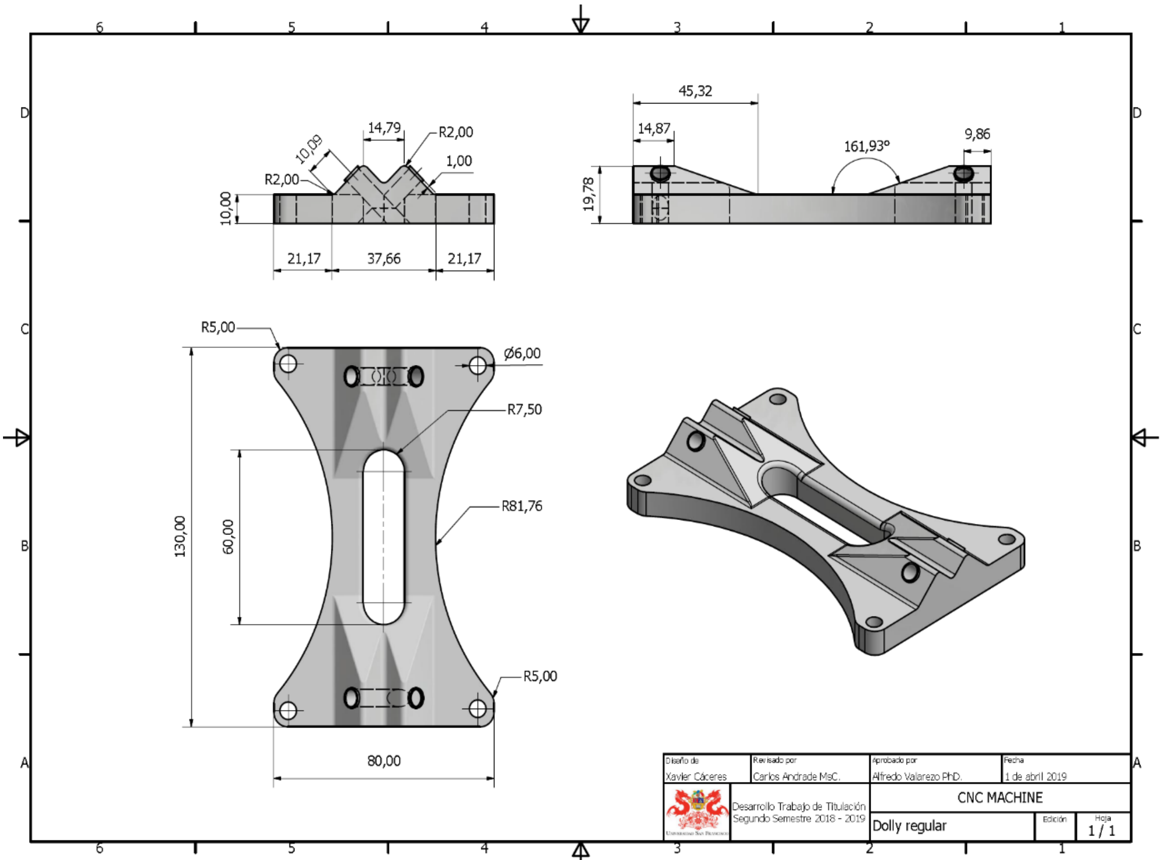
The mechanical components such as the ball screws, bearings and support beams need to be replaced once their components lifetime is achieved or any sign of malfunction is presented. Under normal operation conditions the user need to replace the mechanical components following the next table:

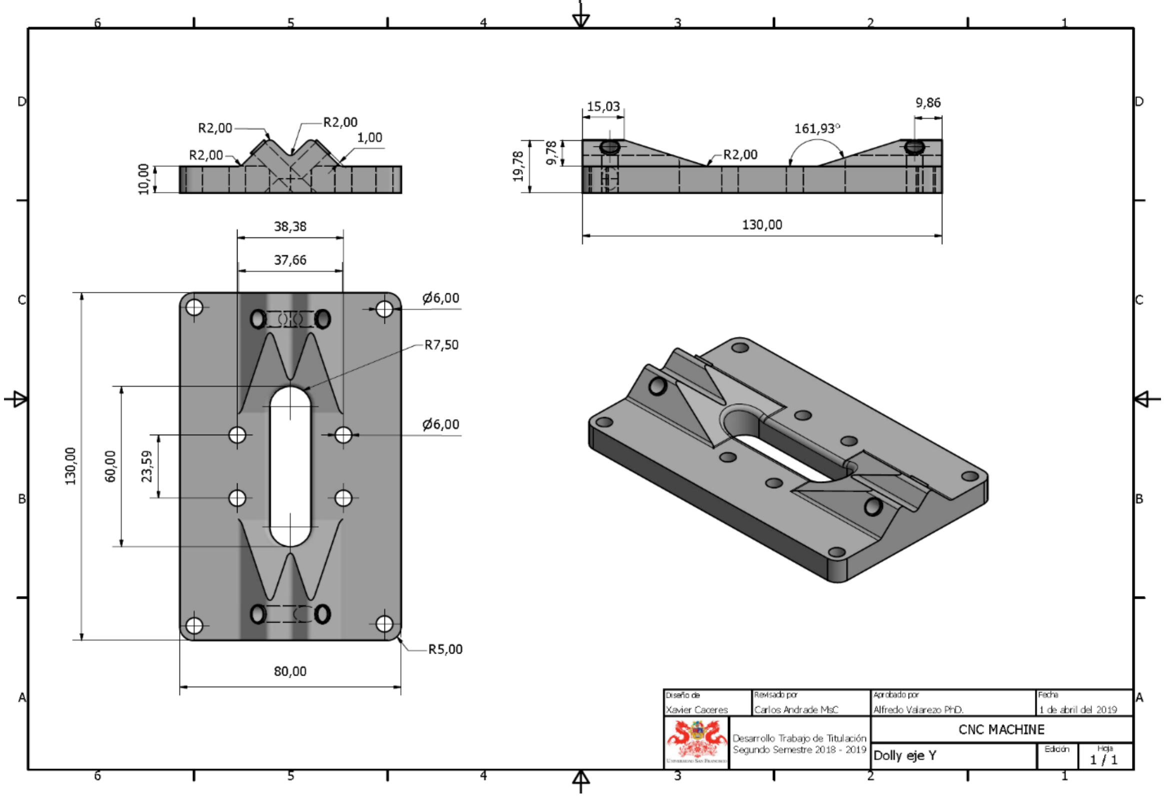
Table 9. Mechanical components replacement time

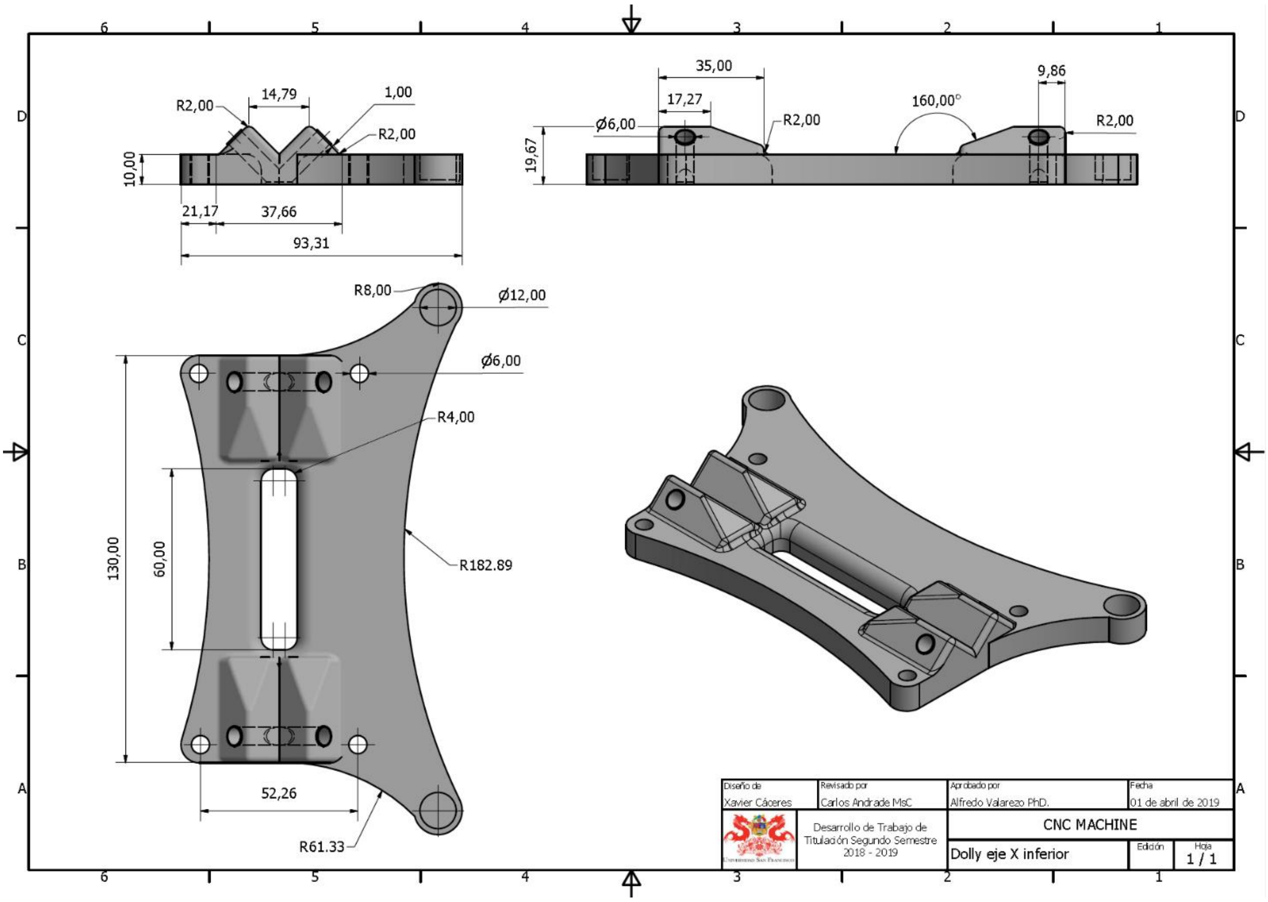
Component	Replacement time
Ball screw	Every 20000 hours or 10 years
Bearings	Every 20000 hours or 10 years
Support beams	Wear and tear presented

Other components, such as the 3D printed parts should be replaced if the machine is operating in temperatures higher than 40°C, or if the weight of the structure is modified.

APPENDIX C: DETAILED DRAWINGS







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Ø12,00
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R182.89
130,00
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52,26
R61.33
Diseño de
Xavier Cáceres
Revisado por
Carlos Andrade MsC
Aprobado por
Alfredo Valarezo PhD.
Fecha
01 de abril de 2019
Desarrollo de Trabajo de Titulación Segundo Semestre 2018 - 2019
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APPENDIX D: PROJECT BUDGET

Table 10. CNC Machine budget

Quantity	Description	Unit Cost ($)	Total Cost ($)
1	Square section ASTM A36 tube	6.8	6.8
2	Nema 17 stepper motor	25	50
2	Nema 23 stepper motor	75	150
3	Driver TB6600	35	105
1	Arduino Mega	25	25
1	CNC Shield Ramps 1.4	14	14
3	Inductive sensors	45	135
46	606 zz bearings	1.34	61.64
3	Kg of PLA 3 mm	40	120
75	Anti-Vibration nuts	0.06	4.5
75	Bolts	0.06	4.5
3	Precision ball screw RM 1605 1500 mm	84.86	254.58
1	Precision ball screw RM1605 250 mm	52.2	52.2
4	Linear bearings	12.5	50
1	Power supply 12V 25A	21.99	21.99
1	Power supply 36V 10A	48	48
1	1-W laser module	85	85
1	500W milling motor	115.98	115.98
1	Control box	20.15	20.15
1	LCD Shield	25	25
1	Milling bits set	26.98	26.98
1	Stainless steel type C beam	50	50
1	25 m cable	20	20
		Total	**$1419.32**