Chapter

Technological Development of CNC Machine Tool for Machining Soft Materials

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Abstract

In recent years, the process carried out in the GACIPE research group is related to the development of the base technology of the manufacturing and metalworking industry. The machine tools that are vital for the consolidation and competitiveness of the industry in any country has been approached through two approaches: The design and construction of the new machine. In this aspect, the modeling of the structure and the displacements' parameterization allows defining the precision of the movements and the rational use of energy. The adaptation and repowering of a used machine. In this approach, the recovery and technological updating proposed to recover its performance, becoming an excellent alternative to improving and perfecting the production of a company. In both cases, the CNC milling machine tools are controlled by free software. The application proposed is mechanized in soft materials.

Keywords: CNC, modeling, repowering, free software, competitiveness

1. Introduction

Modern industry demands more precise and complex products that meet high-quality standards and protocols, using high-performance technological tools such as CNC machine tools. That according to Oxford Economics, the principal manufacturers and consumers worldwide are China, United States The United States, the European Economic Community, India, Brazil, and Japan. These countries have greater competitiveness in world industry [1]. India last decade has had accelerated growth in the consumption and the production of machine tools above 8 percent per year. That is a consequence of the incentives and policy change of the Indian government focused on the constitution of a park of machine tool development and the creation of a center of excellence in machine tools and production technologies [2]. In Germany, the area of machines and equipment is the second most important industrial sector. The country has become a technological engine that distinguishes itself as a high-tech nation worldwide [3]. The United States has distinguished itself as one of the leading exporters of machinery worldwide, being the principal supplier to China in recent years, demonstrating the big industrial capacity to develop machine tools. That equipment that par excellence is the basis for catapult the industrial production of a country [4]. In Latin American countries, MIPYMEs prioritize automation and technological development of machine tools, specifically in Colombia, MIPYMEs represent 94 percent of the industry, where most of the manufacturing processes of MIPYMEs in the metalworking sector are carried out in conventional machine tools [5].

2. CNC machine tools prototype

This section presents the design and development of a prototype of a CNC Milling Machine Tool in its mechanical, electrical, and electronic components and graphical interface.

2.1 Works modeling in CNC machine tools

The different publications scanned in the last ten years to analyze and study structural design in machine tools and cutting techniques. In [6] theoretical 3D model is presented that determines the instantaneous machining stresses generated by the cutting action, presenting the stress distributions in the body of the CNC machine. In [7] proposes a model about the instantaneous cutting forces in 5-axis machining systems per milling machine and identifies the machine's operating parameters to minimize machining error. In [8] explains the model to machine a prismatic workpiece whose objective is to evaluate each component of the machine's power absorption and its relationship with the cutting parameters. In [9] requires a methodology for optimizing the energy consumption to control the machine in the machining of the part is presented. That model is based on historical operating data. In [10] exposes method of defining parameters for NC and machining systems to allow energy efficiency with the least possible error in constructing the resulting part. In [11] proposes a mathematical model based on the cutter's numerical discretization, including the advance and inclination angles. This model is applied in certain typical conditions of a 5-axis machine. In [12] shows a method of cutting stability, the solution is proposed for milling type in multi-axis machines using the general projective geometry technique representing the cutting tool by an envelope of point clouds. In [13] presents a three-dimensional machining model that validates the conventional machining method taking into account the type of cut (uppercut milling, descending cut milling, milling style). Also, The machine used the thermal camera to observe the effective cut depth, shear force, and roughness. In [14] proposes a new cutting operation on a lathe called oriented cutting that consists of a cutter with a straight edge without inclination but oriented with an angle different from 90 degrees; tests show the influence of the edge of the tool on the forces of cut.

2.2 Structure of CNC prototype

In the development of the project, the modeling and mechanical design of the structure of the machine (**Figure 1**) is fundamental, taking into account the accessories of the machine such as servo motors, servo drives, sensors, guides, and sources that allow the movement of its axes speed and precision.

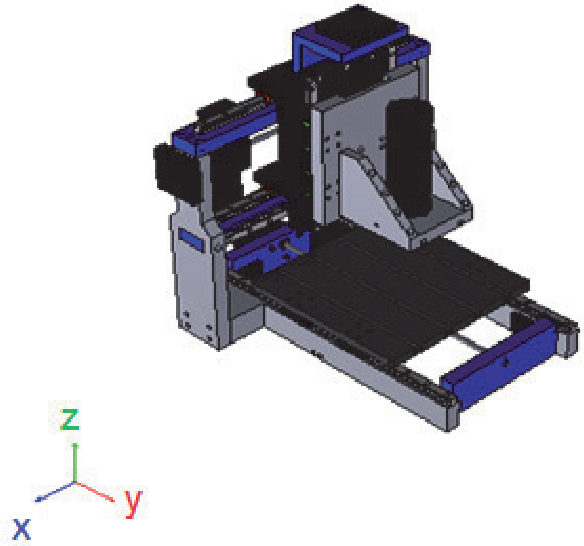


Figure 1.
Isometric CNC milling machine.

The structure has a frame, cross slide, table, bridge that supports articulation of the machine's three axes depending on to develop the pieces' machining. The table has a grooved surface on which the part to be shaped is held. The table is also supported by two carriages that allow the table's horizontal longitudinal movement on the transverse carriage (x-axis). The bridge is a cantilevered piece in the frame; there are also hardened and ground guides for vertical movement (y-axis). Some lunettes were supports of the horizontal movement axis (z-axis).

2.3 Development of the structure of the CNC machine

The machine was developed in a machining center from the model, taking into account the criteria and conditions obtained in the design and simulation of the structure to have robustness and precision in movement, in **Figure 2** you can see part of the real CNC milling machine armed consisting of the bridge, the cross carriage, the motor, and the guides. As shown in **Figure 2**, the machine's structure is configured as a vertical milling machine in which the table has movements in the x and y axes, and the motor with the spindle moves in the z-axis.

Figure 2.
Real CNC machine.

The machine structure was designed by modules and its construction in SAE 1020 plain steel material whose thickness is not less than 2.54 centimeter and with a manufacturing error of 10 micrometers.

2.4 Parameterization of movement of the CNC machine

The procedure for machining in CNC machine tools for milling machines with a fixed height table, horizontal or vertical spindle (**Figure 3**) has been sought, and the CNC machine is parameterized according to [15–17] with the following guide:

Verification of the straightness of the vertical and displacement of the spindle head. Tests are performed on a 155 mm stroke.

Measurements are made in the area tour, yielding the following results in **Table 1**.

The results were showed a variation lower than the admissible one (0.025 mm). This was measured in a length of 155 millimeters. A test carried out to verify the flatness of the table surface (**Figure 4**), in a 28x30 mm extension measurements, are made in the area tour, yielding the following results in **Table 1**. The practice was yielded the following results in different points of the said area, according to **Table 2**.

Figure 3.
Displacement straightness check.

Displacement mm	Displacement error mm	Permissible error mm
10	0.005	0.025
75.25	0.01	0.025
155	0.015	0.025

Table 1.
Spindle vertical travel.

Figure 4.
Verification of the surface flatness of the table.

Coordinates mm	Real error mm	Permissible error mm
0,0	0	0.05
0,150	0.03	0.05
0,280	0.025	0.05

Table 2.
Flatness.

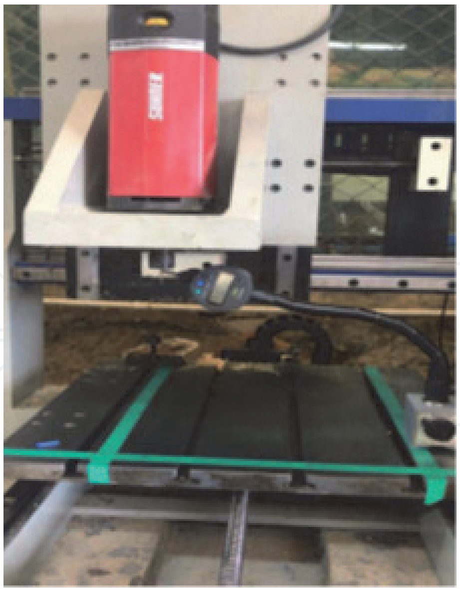


Figure 5.
Checking the radial rotation of the inner core.

The data was obtained in the test does not exceed the maximum allowable difference of 0.05 mm. The measurement of the radial jump of rotation of the inner core at the cone's exit is made (see **Figure 5**).

The test was resulted in the following measurements according to **Table 3**.

The data was obtained in **Table 3** indicate that it does not exceed the admissible difference of 0.02 mm during normal operation of the spindle.

Proof	Measurement mm	Minimum error mm
1	0.02	0.02
2	0.01	0.02
3	0.02	0.02

Table 3.
Measurement of radial jump in the spindle.

3. CNC machine tools repowering

This section has presented the adaptation, reconditioning, and tuning of a used CNC machine tool.

3.1 Fine tunning CNC machine repowering

The experience of building a prototype of a CNC milling machine has been allowed to consider that it can apply the appropriate knowledge in used CNC machines that currently inoperative. Therefore, among the many technologically outdated CNC machines that SENA has, a CNC milling machine has been chosen EMCO brand didactic, used at the time to carry out academic activities with the institution’s students. The conditions and characteristics of the machine are presented below in **Table 4**.

For the CNC machine to repower selected, its mechanical component (structure and mechanisms) must be functional and, as far as possible, close to its factory conditions, this allowed choosing the machine that is observed in **Figure 6**, The hardware of which was in good condition. However, some mechanical components were missing, and the electronic, electrical, and software module obsolescence.

The machine of **Figure 6** has been thoroughly inspected to define the roadmap for the recovery of the machine; therefore, the problems detected are presented below:

- The transmission system of movement towards each of the axes is carried out using a toothed belt and two pinions with a mechanical ratio of 2: 1. So, the torque is incremented but the speed of displacement is reduced.

- - Elements such as gears, screws, supports, bearings, motors, guides, and bases were presented a considerable level of oxidation, preventing adequate movement and increasing the error tolerance in the axes’ displacement by approximately 10 percent.

- During previous interventions, the ball screw of the “Y” axis and the movement transfer pinion of this same axis were not reintegrated into the machine, leaving it incomplete.

To mitigate mechanical difficulties, corrective maintenance related to the design, manufacture, and implementation of the missing parts is carried out;

workspace in X, Y, Z [mm]	Spindle power at 2000 rpm [w]	Ball screw pitch [mm]	Accuracy of each axis [mm]
200,100,200	440	1.5	0.01

Table 4.
Features repowered CNC machine.

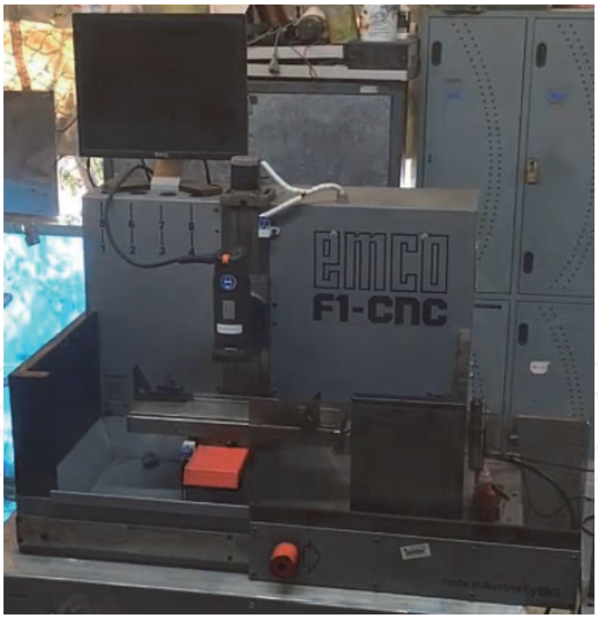


Figure 6.
CNC machine repowering.

subsequently, preventive maintenance is carried out to remove the oxide present and lubricate all the movement mechanisms; Once these corrections have been made, a mechanically adequate CNC milling machine is available to intervene in its entire electrical and electronic operating system.

3.2 Design and implementation of the electrical and electronic system of the repowered machine

Due to the service time of the milling machine, there are drawbacks such as shorts in the power circuit of the motors, failures in the control panel membranes, voltage drops in the power source due to problems in the voltage regulators; on the other hand, the software present in the machine is not compatible with the commercial applications that are currently used for this type of system, the main difficulty regarding compatibility is that the data access to the system is done using an obsolete technology (floppy disk 3/2), so the control card was designed and replace, the drivers and the user interface to recover their initial functions and even improve their operability.

A control and power board is implemented, see **Figure 7**, responsible for linking and optocoupler the drivers that control the motors of each of the axes with the instructions sent from the CNC software in the computer and sensors of end of career of the machine, stop of emergency and other elements that make up the system.

The machine's electronic system was made compatible with the LinuxCNC software; therefore, an optocoupler control interface (**Figure 7A**) has been designed and implemented connected to the parallel port of the pc. The signals obtained from the parallel port are input signals from sensors and output signals that enable actuating actuators. In the output signals, the power system of **Figure 7B** is used to control the actuators as servo motors and step motors responsible for moving the axes that position the milling cutter for machining development.

3.3 Parametrization of the repowered machine

For the execution of a machining production process, the CNC machine must meet a series of requirements related to the straightness in the movement of the axes, the flatness of the work table, and the parallelism concerning the cutting tool;

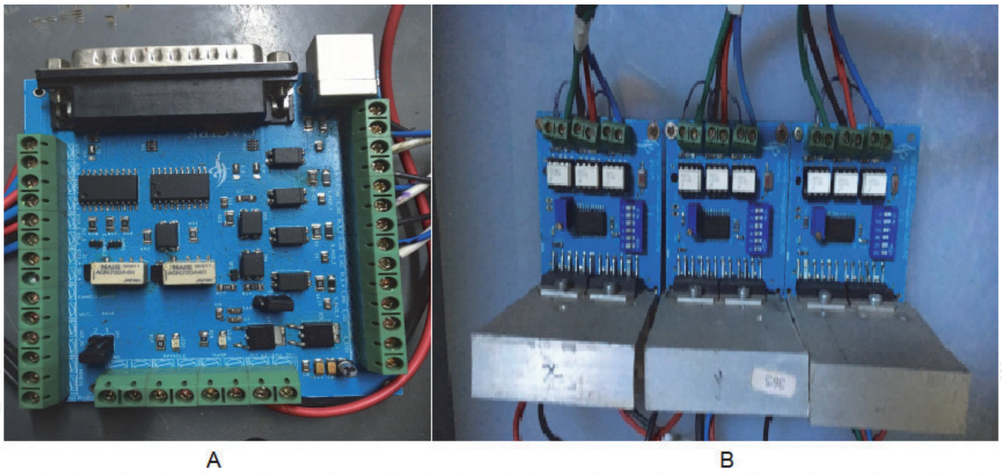


Figure 7.
Electronic system (A) control target (B) power target.

these parameters are necessary to bring the machine to work under the standards of machining parts and are verified by the following procedure:

To corroborate the straightness of the z-axis displacement, a dial gauge is positioned and measured concerning a square that is firstly parallel to the X-axis and later parallel to the Y-axis to verify that the displacement is strictly vertical and comply with the allowable error, which is 0.025 mm in a maximum length of 300 mm offset.

The table surface's flatness is measured with a level of precision where the tolerance cannot exceed 0.02 mm for every 300 mm of length between measurements.

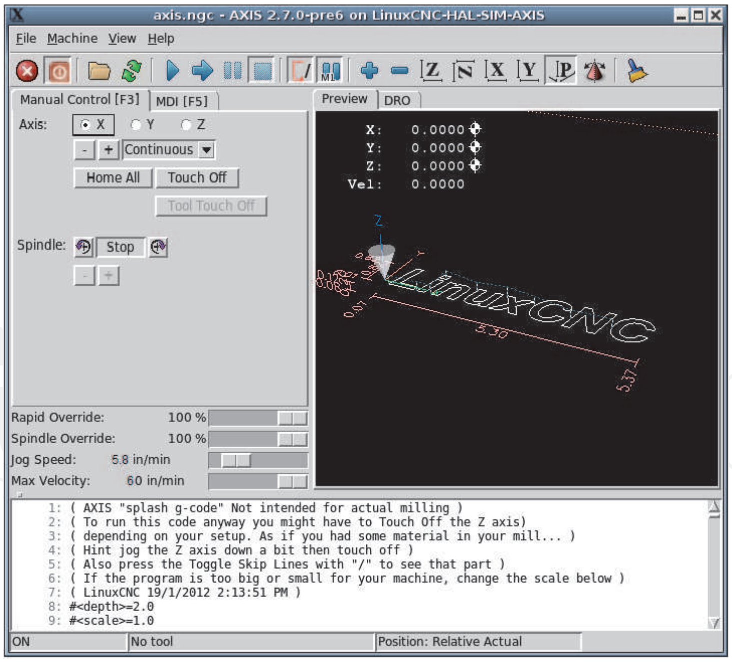
The proceeding must guarantee the parallelism of the surface of the work table concerning the cutting tool, so the dial gauge is placed at its height (see **Figure 8**) and measurements are made along the length and width of the surface; the error cannot be greater than 0.025 mm for every 300 mm between measurements.

This procedure is applied to the machine and the results observed in **Table 2** are obtained, where the data are within the admissible limits to carry out a machining process.

3.4 Software selection and coupling with the CNC machine repowering

In the first instance, tests are carried out with the Mach3 software to verify the compatibility of the control card and the drivers with commercial software for the control of a CNC; the system presents good performance; However, the Mach3 is a demo version with limitations, for this reason, a search is carried out, finding some licensed software such as MasterCAM, SolidCAM, CAMWorks, among others, which were discarded because the license is very expensive, so, the best option has

Figure 8.
Flatness teste.



X: 0.0000
Y: 0.0000
Z: 0.0000
Vel: 0.0000

Rapid Override: 100 %
Spindle Override: 100 %
Jog Speed: 5.8 in/min
Max Velocity: 60 in/min

```
( AXIS "splash g-code" Not intended for actual milling )
( To run this code anyway you might have to Touch Off the Z axis)
( depending on your setup. As if you had some material in your mill... )
( Hint jog the Z axis down a bit then touch off )
( Also press the Toggle Skip Lines with "/" to see that part )
( If the program is too big or small for your machine, change the scale below )
( LinuxCNC 19/1/2012 2:13:51 PM )
#<depth>=2.0
#<scale>=1.0
```

Figure 9.
LinuxCNC interface.

focused the search on open architecture software (Open Architecture CNC), finding that they handle great scalability, are freely distributed and present excellent compatibility with other software related to the manufacturing process and with the different CNC systems.

An application based on the Linux Ubuntu V10.04 operating system called LinuxCNC is selected, see **Figure 9**. The LinuxCNC has an architecture for the numerical control of CNC machines based on the RT-Linux kernel for the execution of instructions in real-time, with a capacity to control up to nine axes; Some works carried out with LinuxCNC demonstrate the capabilities and scope of the software such as those observed in [18–21], another application is observed in a robotic arm for to perform surgical procedures in [22], also shows precision and reliability in CNC systems as in [23].

4. Application used in the two machine tools (prototype and repowered)

To determine the response of machine tools, different types of parts have been machining. The tests have allowed knowing the real behavior of the CNC machines.

4.1 Machining tests to adjust the operations of CNC machines

During the machine set-up process, the relevant materials to be machined have been defined, taking into account the drive element's capacity (spindle) on both CNC machines. Therefore, although the machines' infrastructure allows machining in hard steels, there is a limitation in the spindle with steels. Thus, the tests will be carried out on 3000 series aluminum. This material has manganese as its main alloying material, which allows for good machinability.

To determine the optimal operating parameters; The speeds of movement of the axes and the revolutions per minute of the spindle are calculated using the following equations:

$$n = 1000(v)/d\pi \tag{1}$$

$$f_r = f_z n Z \tag{2}$$

$$T_m = (L + 2A)/f_r \tag{3}$$

$$A = d/2 \tag{4}$$

Where n = spindle speed in rev/min, v = cutting speed in m / min, d = diameter of the cutting tool in mm, f_r = feed rate in mm/min, Z = number of cutting edges of the tool, f_z = feed per edge in mm, T_m = milling time in min, A = approach distance to hook the cutter to the material in mm, L = Milling length in mm. Note that Eqs. (2), (3) and (4) are only valid for milling operations.

The purpose of both the prototype machine and the repowered machine is to develop parts and structures for robotics applications through face milling. Initially, a piece numeric is designed simple, using a 4 mm flat milling cutter for roughing and a two-edged round milling cutter for finishing, both made of carbon steel, in this development of low complexity parts. The real piece is obtained with the design dimension proposed in the CAD (see **Figure 10**).

Figure 10 shows the machining process of a numerical figure at various times from the beginning of **Figure 10A**, during **Figure 10B** and **C**, and the end of **Figure 10D**. This machining test was applied with the following machining operation parameters (see **Table 6**).

This information is obtained from several tests developed with the same design seeking to optimize the variables used in the LINUXCNC to achieve the materialization of the CAD (see **Figure 11**).

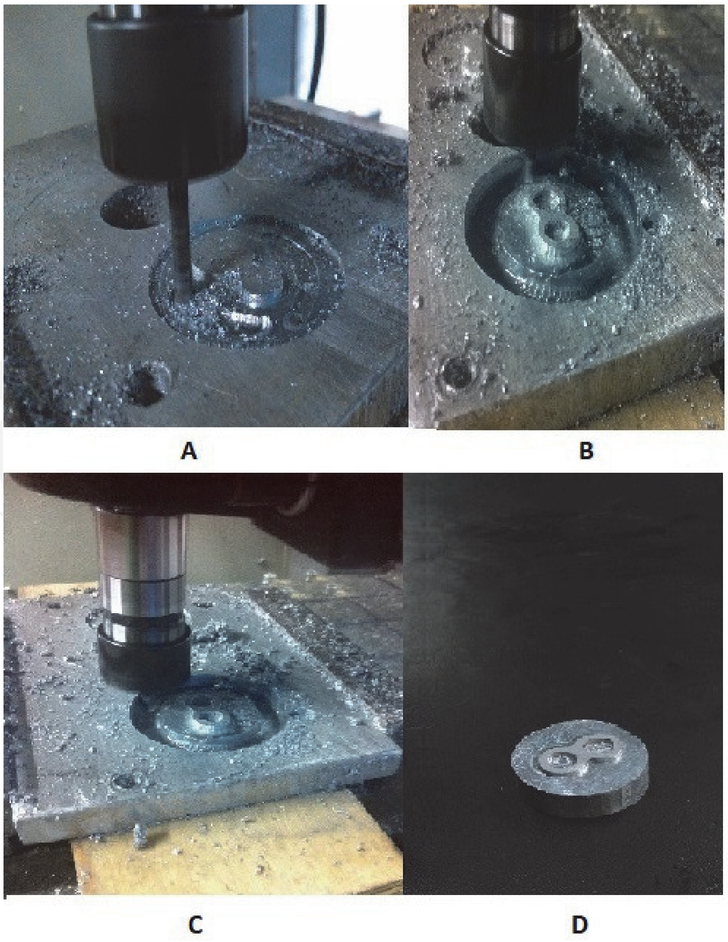


Figure 10.
Alphanumeric part machining process (A) initial machined part. (B) Intermediate part machining (C) intermediate machining of the part figure (C) intermediate machining of the part contour (D) final machining of the part.

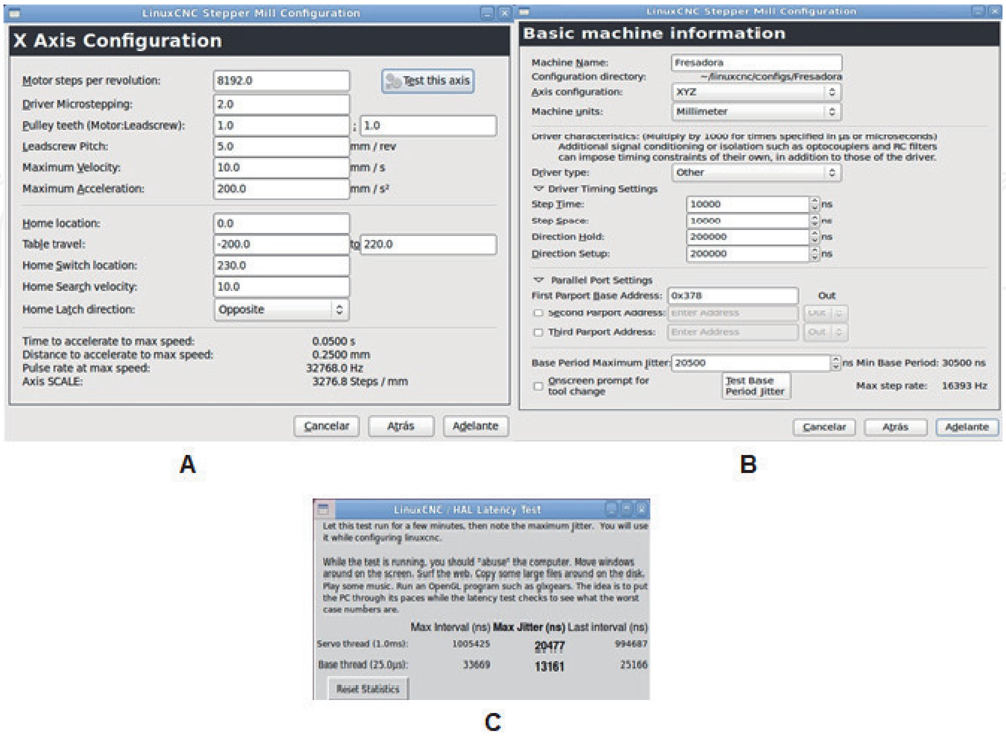
Description	Distance between measures [mm]			
	Ref	**100**	**200**	**300**
Z axis straightness with respect to x	0	0.004	0.012	0.019
Z axis straightness with respect to y	0	0.002	0.004	0.007
X-axis clamping table flatness	0	0.006	0.011	0.015
Y-axis clamping table flatness	0	0.002	0.01	0.018
Parallelism with respect to the x axis tool	0	0.003	0.007	0.01
Parallelism with respect to the y axis tool	0	0.004	0.007	0.009

Table 5.
Test scores.

Description	Process characteristics			
	n [rev/min]	**f_r[mm/min]**	**T_m[min]**	**v [m/min]**
Roughing of material	6366	63.66	3.01	80
Surface Finishing	7957	15.9	31.44	100

Table 6.
Fine tunning.

In **Figure 11A**, shows the configuration of the axes. Parameters are defined as steps per revolution of the machine, the relationship between the motor shaft and the ball screw, the screw pitch, the speed and acceleration of the axis calculated based on the basic configuration information (**Figure 11B**). The axis length parameters and selection of the physical and virtual location of the home are configured. This menu is verified the entered configuration is correct by a test. In the basic information window of the machine, enter the name of the machine, the number of



X Axis Configuration

Motor steps per revolution: 8192.0
Driver Microstepping: 2.0
Pulley teeth (Motor:Leadscrew): 1.0 : 1.0
Leadscrew Pitch: 5.0 mm / rev
Maximum Velocity: 10.0 mm / s
Maximum Acceleration: 200.0 mm / s²
Home location: 0.0
Table travel: -200.0 to 220.0
Home Switch location: 230.0
Home Search velocity: 10.0
Home Latch direction: Opposite
Time to accelerate to max speed: 0.0500 s
Distance to accelerate to max speed: 0.2500 mm
Pulse rate at max speed: 32768.0 Hz
Axis SCALE: 3276.8 Steps / mm

Basic machine information

Machine Name: Fresadora
Configuration directory: ~/linuxcnc/configs/Fresadora
Axis configuration: XYZ
Machine units: Millimeter

Driver characteristics: (Multiply by 1000 for times specified in µs or microseconds)
Additional signal conditioning or isolation such as optocouplers and RC filters can impose timing constraints of their own, in addition to those of the driver.

Driver type: Other
Driver Timing Settings
Step Time: 10000 ns
Step Space: 10000 ns
Direction Hold: 200000 ns
Direction Setup: 200000 ns
Parallel Port Settings
First Parport Base Address: 0x378 Out
☐ Second Parport Address: Enter Address Out
☐ Third Parport Address: Enter Address Out
Base Period Maximum Jitter: 20500 ns Min Base Period: 30500 ns
☐ Onscreen prompt for tool change
Max step rate: 16393 Hz

Let this test run for a few minutes, then note the maximum jitter. You will use it while configuring linuxcnc.

While the test is running, you should "abuse" the computer. Move windows around on the screen. Surf the web. Copy some large files around on the disk. Play some music. Run an OpenGL program such as glxgears. The idea is to put the PC through its paces while the latency test checks to see what the worst case numbers are.

	Max Interval (ns)	Max Jitter (ns)	Last interval (ns)
Servo thread (1.0ms):	1005425	20477	994687
Base thread (25.0µs):	33669	13161	25166

Figure 11.
LinuxCNC parameters (A) axes configuration. (B) Machine information. (C) Latency test.

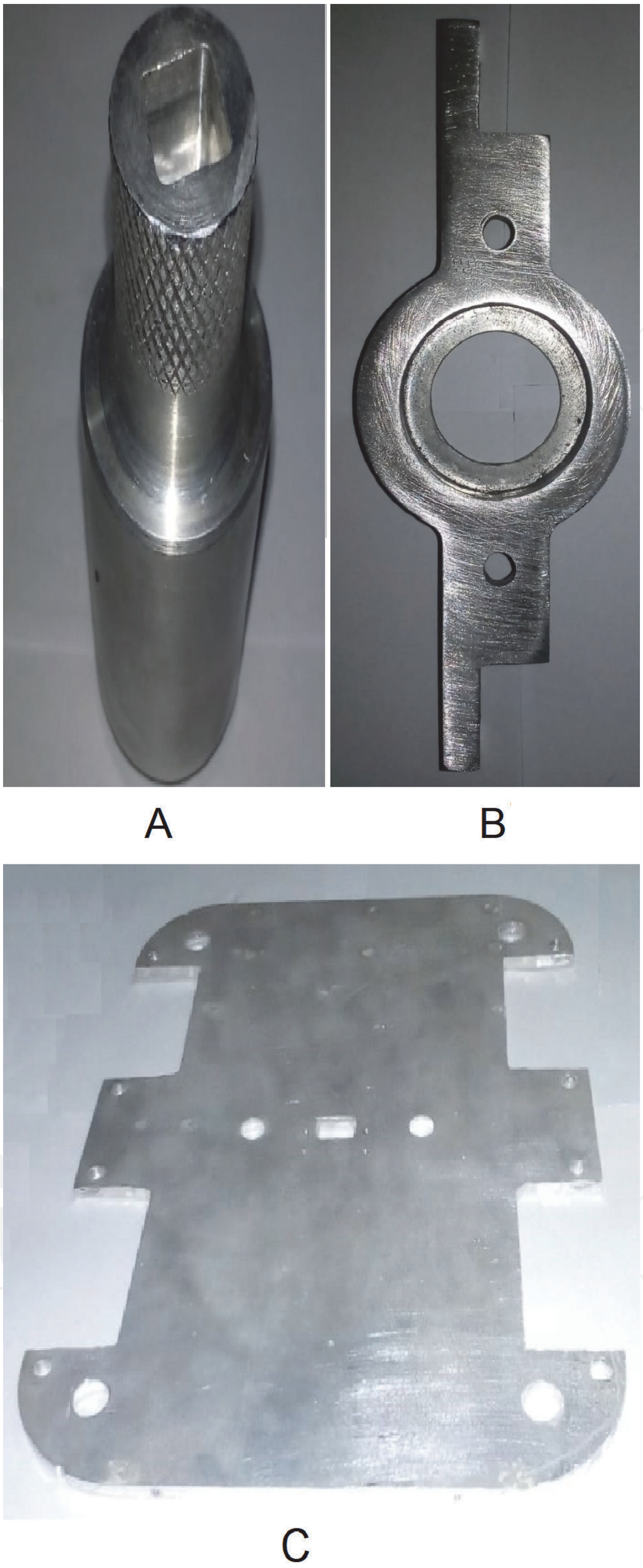


Figure 12.
Machined parts (A) motor shaft. (B) Shaft bracket. (C) Platform.

Operation	**Piece**		
	Figure 12A	**Figure 12B**	**Figure 12C**
Planned	no	yes	yes
Squared	yes	yes	no
Contoured	no	no	yes
Boxed	yes	yes	no

Table 7.
Operations used in the milling of robotic parts.

axes, and the units with which you want to work; To select the type of driver, the software provides some brands of manufacturers that have preset values; however, Linuxcnc allows the selection of a general type of driver and recommends standard values in which most of the drivers work properly. To find the system's maximum response time, the latency test is used (**Figure 11C**), where a test is verified the response capacity of the PC intended to operate the machine.

Subsequently, structural parts of a mobile robot were made for a real application in the health sector. The proposed parts have a more complex and larger structure; Therefore, 6 mm flat mills are used in cutting, and four-edged round milling cutters are used in the finishing. The machined parts fulfill the function of making traction and generating stability in the robot. According to what was projected in the CAD design, the real components are assembled in the robot structure without any difficulty and fully comply with the robotic system's function (see **Figure 12**).

The pieces of **Figure 12** are produced using machining parameters of **Table 6**, and **Table 7** shows some operations of machined pieces.

Table 7 is about machining pieces of **Figure 12**, incorporated in the programming for prototype and re-powered CNC milling machine. In the milling of a piece is normal to find many types of machining operations. The piece more complex, according to **Table 7**, is the piece describes in **Figure 12B**. So the piece of **Figure 12B** applied various operations such as Planned, Squared, and Boxed.

5. Conclusions

In the development of the modeling of a CNC machine proposed in the works found [6, 8, 11] has been detected for the most part that energy optimization has started from a robust and functional structure as a fundamental premise. This aspect has been taken into account in this project in the design criteria used in the configuration of the structure of the CNC machine type milling machine.

In the construction and commissioning of the CNC machine have been considered in some works [7, 9, 10], the parameterization and recognition of the functionality as a fundamental development, so, three aspects have been put into practice in the present project: the straightness of the displacement of the coordinate axes, the flatness of the table surface and the radial jump of rotation of the inner core at the exit of the spindle. In the results of prototype and repowering was observed (see **Tables 1–3**) a good performance.

According to **Table 5**, the repowered CNC machine tool has been brought to an operating point similar to the factory's behavior. This allows the technological development to be exposed as a solution proposal with viable free software to update the CNC machine tools. So, the mechanisms and mechanical functionality of the machine are in good condition, and its recovery is viable.

The mechanization tests for both machine tools present the millimeter construction of robotics part in aluminum. The precision of prototype and repowered machines is achieved by determining the values of the machining parameters. These data are presented in **Table 6**. The pieces are possible to mechanize with a maximum area of 25 x 25 centimeters. The operations used in the machines'programming are Presented in **Table 7**, furthermore, the description is dimensioned the degree of complexity of each of the parts' machining.

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