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Development of a CNC plasma cutting machine: design and construction for didactic purposes

Desenvolvimento de uma máquina CNC de corte a plasma de tamanho reduzido para aplicações didáticas

Richard Thomas Lermen(1); Rafael Mognon Dos Passos(2); Camila Pereira Lisboa(3); Thaís Letícia Pilotto(4); Rodrigo de Almeida Silva(5)

1 Doutor em Engenharia, ATITUS Educação, Passo Fundo, RS, Brasil.
E-mail: richard.lermen@gmail.com
2 Engenheiro Mecânico, ATITUS Educação, Passo Fundo, RS, Brasil.
E-mail: rmpmognon@gmail.com
3 Mestre em Engenharia, ATITUS Educação, Passo Fundo, RS, Brasil.
E-mail: camila.lisboa@atitus.edu.br
4 Mestranda em Engenharia Civil, ATITUS Educação, Passo Fundo, RS, Brasil.
E-mail: thaislpilotto@gmail.com
5 Doutor em Engenharia, ATITUS Educação, Passo Fundo, RS, Brasil.
E-mail: rodrigo.silva@atitus.edu.br

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Abstract

The design and construction of CNC plasma cutting machines plays a key role in modernizing and optimizing industrial processes, providing significant benefits in terms of precision, efficiency and versatility. This technology makes it possible to cut a wide variety of materials, mainly metals, enabling the creation of complex, high-quality parts. The aim of this work was to develop a small CNC (Computer Numerical Control) plasma cutting machine for teaching purposes. The machine was designed using SolidWorks software, ensuring greater precision in the choice of CNC components. The CNC was moved in three axes, driven by four Nema 23 stepper motors (one for the x-axis, two for the y-axis and one for the z-axis). Control was via a USB microcontroller which received the cutting commands from a user-friendly software interface, Mach3. A Cut 60 inverter plasma cutting machine was used to generate the cutting plasma. With regard to the plasma cutting process, initial tests were carried out by varying the operating parameters, such as plasma current, cutting speed and torch height. The results showed that the movement of the CNC in the x, y and z axes was partly satisfactory. However, it is necessary to calibrate the y-axis, as the dimensions were not regular when cutting a circumference. Regarding the operation of the plasma, it is still necessary to adjust the parameters to optimize the cutting of metal sheets with different thicknesses.

Keywords: CNC; Plasma cutting; Teaching bench; Automation; Control.

Resumo

O projeto e construção de máquinas CNC de corte a plasma desempenha um papel fundamental na modernização e otimização dos processos industriais, proporcionando benefícios significativos em termos de precisão, eficiência e versatilidade. Essa tecnologia possibilita realizar cortes em uma ampla variedade de materiais, principalmente metais, permitindo a criação de peças complexas e de alta qualidade. O presente trabalho teve como objetivo o desenvolvimento de uma máquina CNC (Controle Numérico Computadorizado) de corte a plasma de tamanho reduzido para fins didáticos. A máquina foi projetada com o auxílio do software SolidWorks, garantindo maior precisão na escolha dos componentes da CNC. A movimentação da CNC foi realizada em três eixos, impulsionados por quatro motores de passo Nema 23 (um para o eixo x, dois para o eixo y e um para o eixo z). O controle foi realizado por meio de um microcontrolador USB que recebe os comandos de corte a partir de um software de interface amigável, o Mach3. Para a geração do plasma de corte, foi empregada uma máquina de corte plasma inversora Cut 60. No que diz respeito ao processo de corte a plasma, foram realizados testes iniciais variando os parâmetros de operação, como corrente do plasma, velocidade de corte e altura da tocha. Os resultados mostraram que a movimentação da CNC nos eixos x, y e z foi satisfatória em parte. No entanto, é necessário realizar uma calibração no eixo y, pois, durante o corte de uma circunferência, as dimensões não foram regulares. Em relação ao funcionamento do plasma, ainda é necessário ajustar os parâmetros para otimizar o corte de chapas metálicas com diferentes espessuras.

Palavras-chave: CNC; Corte Plasma; Bancada didática; Automação; Controle.

1 Introduction

Automation and mechanization of manufacturing processes have played a key role in the advancement of industry (GOMAA *et al.*, 2023). In this context, Computer Numerical Control (CNC) machines have been widely used to increase the efficiency and precision of cutting, drilling and machining operations (MOREIRA, 2022). A specific application of these machines is plasma cutting, which is a technique used to cut materials such as steel, aluminum and other metals (KUDRNA; MERTA, 2017). In this plasma cutting process, a gas is strongly ionized by applying a high-frequency electric current. This results in the formation of a highly energetic plasma jet, which reaches extremely high temperatures. The plasma jet is then directed at the workpiece, where the intense heat melts the material, while a flow of auxiliary gas removes the molten residue. The main advantage of plasma cutting is its ability to handle materials of varying thicknesses, from thin sheets to thicker plates, with speed and precision (MACHADO, 1996). In addition, plasma cutting offers great flexibility in terms of cutting shapes and geometries, making it possible to create complex parts with clean edges and no burrs. This technique has been widely adopted in sectors such as the metallurgical industry, the manufacture of metal structures, shipbuilding and the manufacture of automotive parts (DOS SANTOS CARDOSO; RODRIGUES, 2022).

Although CNC plasma cutting is a powerful and versatile tool, its access and use in educational environments can be limited due to the high cost of commercial machines available on the market. In addition, the lack of technical mastery required to operate and program these machines can pose significant barriers for students and educators (SKOVGAARD JENSEN; ÖZKIL; MOUGAARD, 2016).

Limited access to plasma cutting CNCs for teaching purposes can hinder the development of practical skills and knowledge of students in the fields of engineering, technology and science. The lack of opportunities for hands-on learning can restrict these students' potential for innovation and creativity. In addition, the unavailability of suitable teaching resources can make it difficult to teach these concepts in an attractive and meaningful way (BAENA *et al.*, 2017).

When developing a plasma cutting CNC project for teaching purposes, it is important to consider several aspects. Firstly, it is necessary to understand the basic principles of CNC, including the mechanics of movement, electronic control and software programming. There are various resources available, including online tutorials, books and courses, which can help with this learning process (ALELWANI *et al.*, 2019).

Once the basic principles are understood, the next step is to design the CNC's mechanical structure. This involves selecting and sizing the components, such as linear rails, stepper or servo motors, ball screws and drive units. The design must take into account the desired working area, the rigidity of the structure and other specific requirements for plasma cutting (RAMOS *et al.*, 2018).

In addition, it is important to choose a suitable controller for the CNC. There are several options available, from Arduino-based DIY controllers to more advanced commercial controllers (ALBARRÁN; RAMIREZ; MOLINA, 2012; GIRHE; YENKAR; CHIRDE, 2018). The controller will be responsible for receiving the commands from the control software, interpreting them and sending the correct signals to the motors and other machine components.

As for the software, there are several CNC control program options available. Some are free and open source, while others are commercial (LIU; YAO; LI, 2020). The software makes it possible to create and import drawings and models, define cutting paths, configure cutting parameters and generate G code, which is the programming language used by CNCs. (XU; NEWMAN, 2006).

In the specific case of a plasma cutting CNC, it is also necessary to integrate a gas supply and control system to guarantee the quality of the cut. This includes choosing a suitable plasma generator, as well as configuring the gas parameters, such as pressure, flow and mixing, to obtain the desired results (KORZHYK *et al*., 2022).

Once the CNC plasma cutter has been built, it can be used for a variety of teaching purposes. Students can learn about programming, electronics, mechanics, motion control, materials and manufacturing processes. They can create projects, develop practical skills and explore the application of CNCs in different areas, such as prototyping, making custom parts and metal art (KUMAR *et al*., 2021).

Several academic papers and practical projects have addressed the development of plasma cutting CNCs, but most of them are geared towards the industrial and commercial context, with a focus on efficiency and productivity (DE ALMEIDA *et al*., 2020; MOTA, 2019; NIADA, 2020; OSOWSKI, 2014). Little attention has been paid to the creation of low-cost plasma cutting machines specifically designed for teaching purposes (STANGER *et al*., 2020).

This article aims to fill this gap by presenting the design and construction of a plasma cutting CNC machine specifically designed for teaching purposes. The difference this work makes is that it provides students and educators with a practical, low-cost and easily accessible tool that enables them to explore automation, programming and manufacturing concepts in a didactic and interactive way.

2 Materials and methods

The methodology was divided into three main parts: CNC machine design, CNC machine construction and CNC machine operation. The first stage involved defining the design requirements, selecting the necessary components and drawing up the machine layout. The second stage focused on building the machine structure, installing the electronic components and carrying out initial tests. Finally, the third part dealt with operating the CNC machine, including programming procedures and performing the cuts.

2.1 CNC Machine Design

2.1.1 Definition of Project Requirements

The design requirements for a CNC plasma cutting machine can vary depending on specific needs and applications. However, the following design requirements have been chosen according to pre-existing materials in the ATITUS Education laboratories:

- The working area was 1.0 x 0.8 m (x and y axis) according to an existing structure in the institution's laboratories and a variation of 100 mm in the z axis (plasma torch height variation) due to the 200 mm spindle and torch fixing system.
- As for the cutting speed, the machine's maximum axis travel speed is 3000 mm/min.
- Cutting accuracy was determined according to the stability of the machine, the rigidity of the structure, the quality of the control system, the stability of the plasma arc and other factors.
- The movement system was made using 4 stepper motors, two for the y-axis, one for the x-axis and one for the z-axis.
- The plasma power source was a Lynus LIT 516P multiprocess inverter machine with a cutting current range of 10 to 40 A, which enables cutting of carbon steel sheets up to 12 mm.
- The control system was built using an RNR ECOMOTION CNC microprocessor board and Mach3 software.
- As far as safety is concerned, an emergency stop button and limit switches are to be installed.

2.1.2 Component selection

The selection of components can be divided into two parts: mechanical components and electrical components. Figure 1 shows the main mechanical components used in the project, such as: (a) I-beams (2 with a length of 1.2 m, 2 with a length of 1.0 m and 4 with a length of 0.70 m); (b) 40x40 mm square tube with a length of 1.1 m, (c) 4 20 mm linear guides (2 with a length of 1.2 m - y-axis and 2 with a length of 0.90 m - x-axis); (d) 8 pillow blocks 20 mm and 4 pillow blocks 8 mm; (e) a nut and (g and h) 2 bearings for (f) a 12 mm spindle; a torch clamping system consisting of (o) 2 springs, (k) 2 spacers, (s) 2 linear shafts and (i, j and m) 3 clamping pieces; (n) a z-axis motor clamp; (p) 6 rollers 36 teeth 8 mm; (q) 4 pulleys 36 teeth 8 mm; (r) a 10 mm toothed belt with a pitch of 2 mm; (t) a cutting grid consisting of 10 flat bars 2 mm thick and 1.1 m long; and a z-axis motor coupler.

A description of the electronic components of the CNC plasma cutting machine is essential to understanding the operation and integration of these essential elements. These components have been carefully selected to ensure reliable and precise performance of the CNC machine. Table 1 gives an overview of the electronic components, highlighting their specifications and key functionalities.

In addition to the components shown in Table 1, cables and wires were used to make the electrical connections between the components. Also, a plasma torch cable (with gas inlet and electrical connection) and an earthing cable, which were connected to the inverter power source.

Figure 1. Main mechanical components for building the CNC for plasma cutting

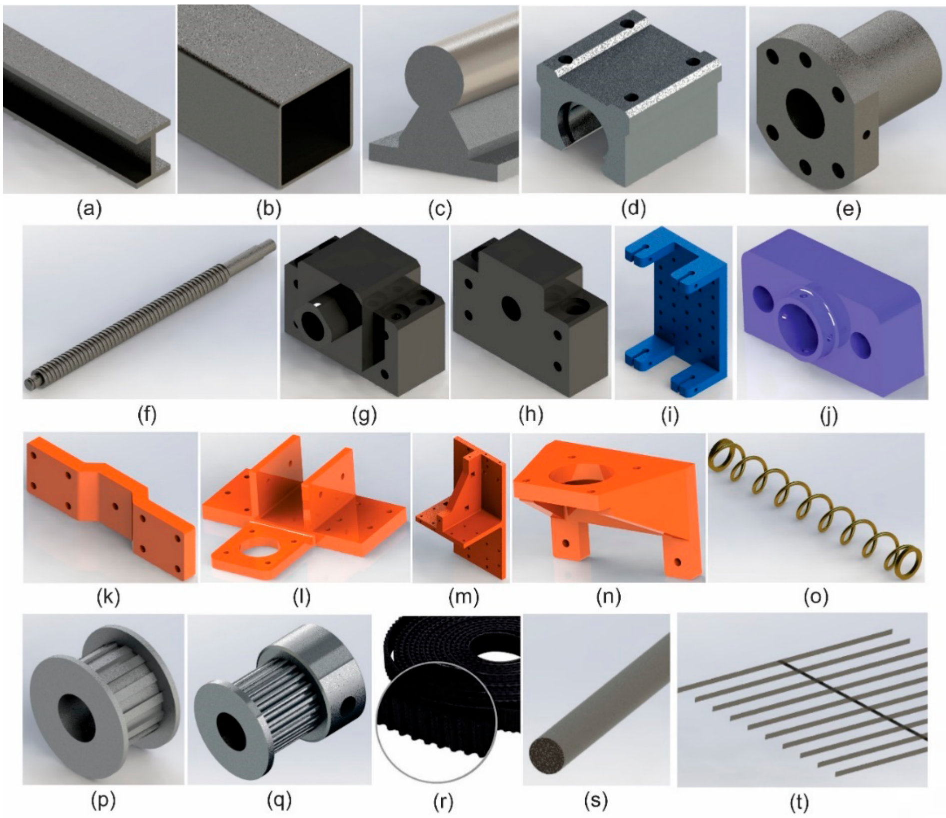
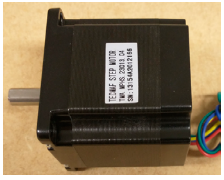
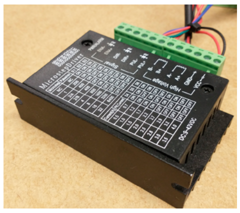
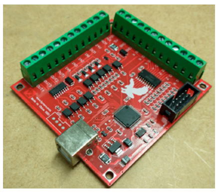


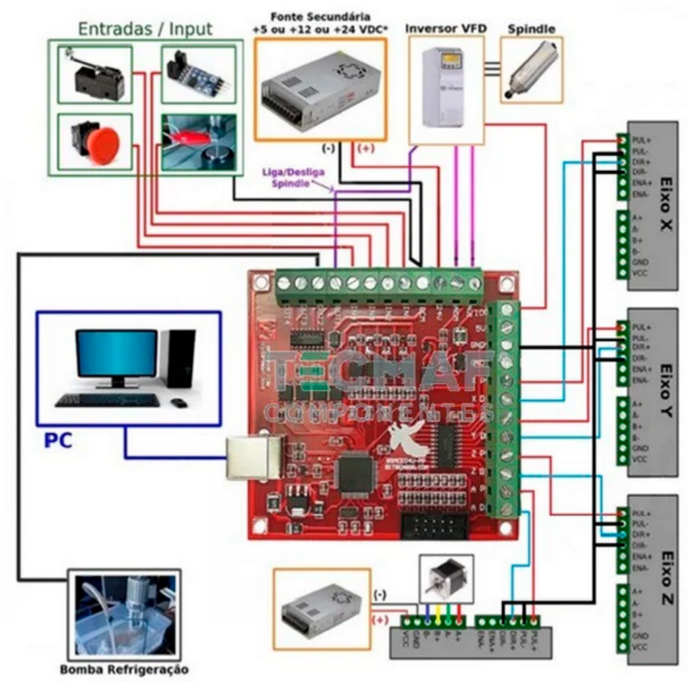
Table 1. Electronic components and plasma cutting

Component	Specifications	Qty.	Image
Stepper motor	Nema 23 - 20 kg	3	
Stepper motor	Nema 23 - 12 kg	1	
Motor drive	TB 6600	4	
Controller board	USB RNR ECOMOTION	1	
Emergency button	Switch Emergency button 10A	1	
Limit switch	5 A 250V	7	
Relay (plasma torch drive)	10A 30VDC	1	
Power supply	24V, 20A switched-mode power supply.	1	
Plasma Cutting supply	Lynus LIT 516P inverter	1	

2.1.3 Installation of Electronic Components

The installation of the CNC plasma cutting machine's electronic components was a fundamental step in ensuring that the machine worked properly. Figure 2 shows an example of the connections to the controller board.

Figure 2. Example of connections with the RNR Ecomotion USB card (TECMAF, 2023).



Below are the main steps involved in this installation:

- The motion controller is the brain of the CNC and is responsible for receiving the commands from the software and sending the signals to the motors. It was installed in a suitable box and connected to the motor drivers.
- The motor drivers were installed according to the manufacturer's specifications and connected correctly to the motion controller and the motors.
- The power supply provides the energy needed to run the CNC's electronic components. This power supply was installed with attention to the voltage and current requirements for the motor drivers, motion controller and other electronic devices.
- To ensure safety during CNC operation, protective devices such as fuses, circuit breakers and emergency buttons are to be installed. These devices will be properly connected to protect the machine and operators in the event of faults or emergencies.
- During the installation of the electronic components, the power cables,

control cables and signal cables had to be connected. These cables were routed in an organized and safe manner, avoiding interference and damage during machine movement.

- After installing the electronic components, tests were carried out to check that all the devices were working correctly. This included testing the motors, checking the communication between the motion controller and the drivers, as well as setting the appropriate parameters in the CNC control software.

Throughout the process of installing the electronic components, it was essential to follow the manufacturer's instructions, ensure the correct connection of cables, avoid short circuits and take the necessary safety precautions.

2.1.4 Configuration and Initial Tests

The initial CNC machine movement and calibration tests were carried out using the Mach3 software. After assembling the mechanical and electronic components, the Mach3 software was configured and integrated into the CNC machine system. Initially, tests were carried out on the movement of the axes, checking that the motors responded correctly to the movement commands. During this stage, the forward and reverse movements and positioning of the axes were evaluated, ensuring that they were aligned and moved according to the programmed coordinates.

Calibration tests were then carried out to ensure the precision and accuracy of the movements. Using a 300mm caliper, predetermined distances were covered on the X, Y and Z axes, checking that the movement corresponded to the coordinates specified in the Mach3 software. In the event of inaccuracies or deviations, adjustments were made to the software settings to correct the movement parameters, such as the resolution of the stepper motors or servomotors, steps per unit, acceleration and movement speed.

These initial movement and calibration tests using Mach3 software were crucial to ensuring that the CNC machine operated accurately and repeatably. At the end of this stage, the machine was ready to be used in plasma cutting operations, providing reliable, high-quality results.

2.2 CNC Machine Operation

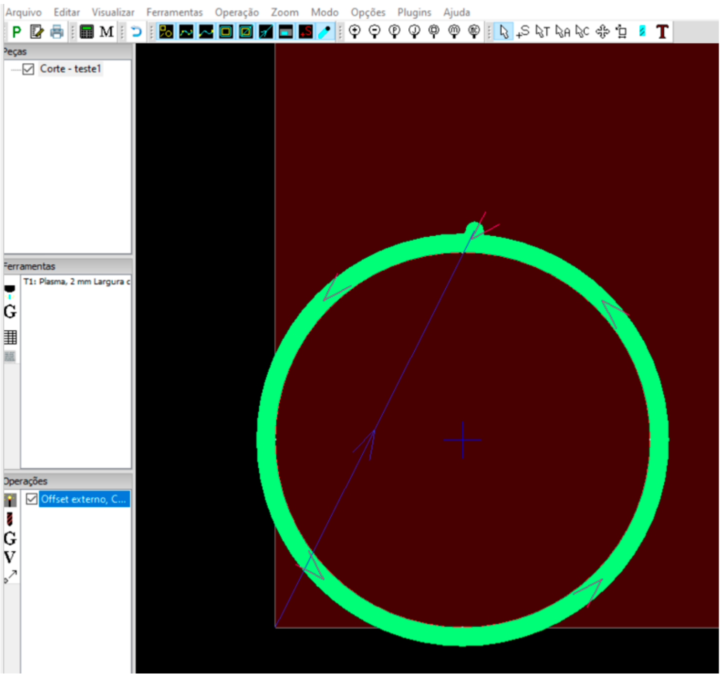
Operating the CNC plasma cutting machine involved programming the SheetCam TNG Development software (Figure 3) and carrying out cutting tests on a 3 mm thick carbon steel sheet. The main steps of this operation are described below:

- Using SheetCam TNG Development software, a drawing file was created containing the geometric elements of the desired cuts. In this case, a circular cut was programmed into the steel sheet.
- In SheetCam TNG Development, cutting parameters such as feed rate,

cutting speed, torch height, plasma current and more are configured. These parameters are adjusted according to the material to be cut and the specifications of the plasma torch.

- After setting the cutting parameters, SheetCam TNG Development automatically generated the G-code, which contains the instructions for moving and driving the CNC machine. This G-code is compatible with the Mach3 software used to control the CNC machine.
- The G-code generated by SheetCam TNG Development was loaded into the Mach3 software, which controls the movements of the CNC machine. The program was configured to follow the instructions in the G-code and make the desired cuts in the steel sheet.
- The 3 mm thick steel plate has been properly clamped in the working area of the CNC machine. It is important to ensure that the plate is level and firmly clamped to avoid unwanted vibrations during cutting.
- With the CNC machine and Mach3 software (Figure 4) ready, the programmed elements were cut. Mach3 sent the movement and drive commands to the machine, which executed the program on the carbon steel plate.
- Once the cutting was complete, the result was visually checked. The accuracy of the cuts, the quality of the edges and compliance with the dimensions specified in the program were evaluated.

Figure 3. *Sheetcam* interface with the drawing of the part to be cut, cutting parameters and G-code



Cutting parameters

Cuting speed: 300 mm/min
Electric current intensity: 50 A
Torch distance/piece: 2 mm
Gas type: compressed air
Gas pressure: 6 bar

G code

```
N0010 (Filename: Corte CNC 7.tap)
N0020 (Post processor: Mach3 plasma.scpost)
N0030 (Date: 29/06/2023)
N0040 G21 (Units: Metric)
N0050 G53 G90 G91.1 G40
N0060 F1
N0070 S500
N0080 (Part: Corte - teste1)
N0090 (Operation: Offset externo, Color 373435, T1: Plasma, 2 mm
Largura de corte)
N0100 M06 T1 F300.0  (Plasma, 2 mm Largura de corte)
N0110 G00 Z10.0000
N0120 X21.2800 Y42.2800
N0130 Z3.0000
N0140 M03
N0150 G04 P0.5
N0160 G01 Z2.0000 F300.0
N0170 G02 X20.0000 Y41.0000 I-1.2800 J0.0000
N0180 G03 X20.0000 Y41.0000 I0.0000 J-21.0000
N0190 M05
N0200 G00 Z10.0000
N0210 M05 M30
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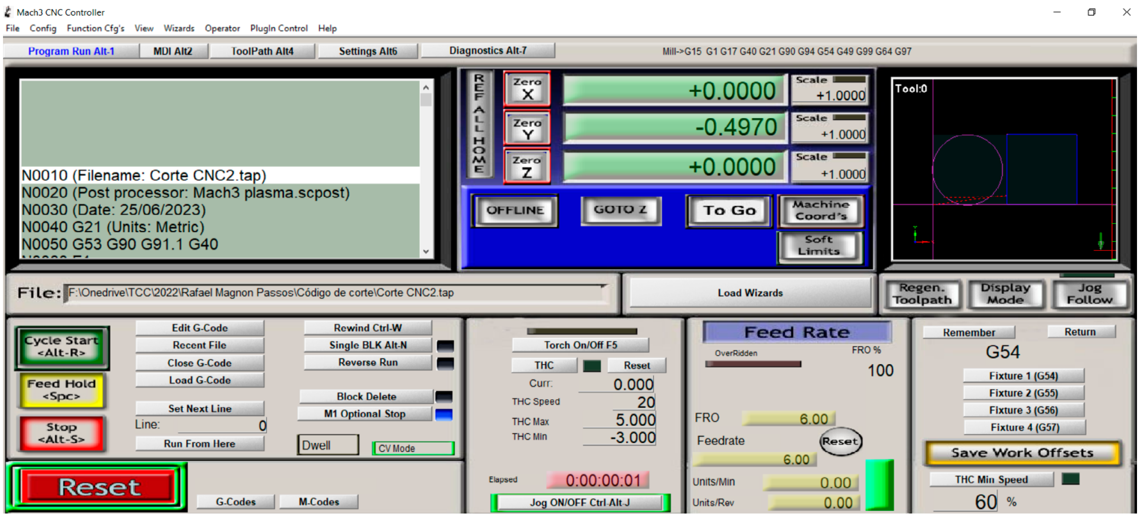
Figure 4. Mach3 interface with the drawing of the part to be cut



3 Results and discussions

This study presents the results and discussions obtained from various stages of research and development. The “Solidworks Project” subheading is divided into an analysis of the structural and functional design of the project, using Solidworks software for modeling. The “Electrical System” section covers the implementation of the electrical and electronic components required for the operation of the Plasma CNC system. The topic “CNC Plasma Prototype” describes the construction and assembly of the physical prototype of the machine, considering the mechanical, electrical and electronic aspects. The “CNC Movement and Calibration Tests” were carried out to guarantee the precision and correct functioning of the CNC machine’s movements. Finally, the “CNC Plasma Cutting Tests” involve evaluating and analyzing the results obtained from using the CNC Plasma system in cutting situations, allowing its efficiency and operational capacity to be gauged. The discussion of the results obtained in each of these areas will provide a comprehensive understanding of the characteristics and performance of the CNC Plasma system developed in this study.

3.1 Solidworks Design

Figure 5 shows the schematic drawing of the plasma CNC, presented in rendered form, but without the inclusion of the electrical parts (cables, wires, power sources, drivers, controller board, etc.). In this representation, the structural and mechanical characteristics of the system are highlighted, providing a clear view of the layout of the main components. The absence of the electrical parts in the rendering allows for a more focused analysis of the machine’s structural elements, such as rails, guides, motors and axes, providing a more precise understanding of its geometry and layout.

This schematic representation was fundamental to the visual understanding of the project and serves as a basis for discussion and analysis of the mechanical aspects of the plasma CNC.

Figure 5. Rendered schematic drawing of the structural part of the plasma CNC

During the 3D modeling of the plasma CNC machine in Solidworks software, some difficulties were encountered. One of the main difficulties was related to the complexity of the plasma CNC components, such as rails, linear guides, motors and axes, which required meticulous attention to detail and technical specifications. In addition, the integration of the different elements of the system, both mechanical and electrical, presented challenges to ensure correct assembly and interaction between the parts. It was also necessary to deal with the suitability of the dimensions and proportions of the components to ensure the functionality and ergonomics of the machine. Throughout the modeling process, adjustments and revisions had to be made to ensure the accuracy and fidelity of the 3D representation of the CNC plasma machine. Despite these difficulties, the use of Solidworks as a modeling tool made it possible to overcome the challenges and obtain a detailed virtual representation of the plasma CNC, which was essential for the development and analysis of the project.

It should be noted that the 3D drawing in Solidworks of the CNC plasma machine will still have to be adjusted with the missing parts (electrical system, movement belts, cable and wire organizer, etc.).

3.2 Electrical System

The electrical system of the plasma CNC has been carefully designed to ensure the correct operation and control of the machine. Figure 6 shows the electrical panel, where the essential components are present, such as the power source for the motors, the drivers, the controller board and the plasma arc drive relay. This current configuration of the electrical panel is in line with what was initially planned, allowing the motors and the plasma system to be properly driven and controlled. However, it is important to mention that the panel is due to be replaced by a larger model, which will accommodate the plasma source, as well as additional safety devices. This upgrade will provide a more efficient organization of the electrical components, as well as ensuring greater protection and safety during operation of the plasma CNC.

3.3 CNC Plasma Prototype

The Plasma CNC prototype developed represents an important milestone in the project, as it is the physical materialization of the theoretical concept and the research and development efforts. The prototype, which can be seen in Figure 7, has a robust and well-built structure with integrated mechanical, electrical and electronic components. The system consists of rails and linear guides that guarantee precise movements in the X, Y and Z axes. High-power motors and drivers allow for agile and controlled movement. In addition, the prototype has a properly configured electrical panel, which includes the power source, the controller board and the plasma arc drive devices. With the prototype in operation, it is possible to carry out plasma cutting tests and assess its ability to produce high-quality results. The development of this prototype represents a significant step forward in CNC Plasma design, paving the way for continuous optimization and improvement of the system.

Figure 6. Plasma CNC electrical system

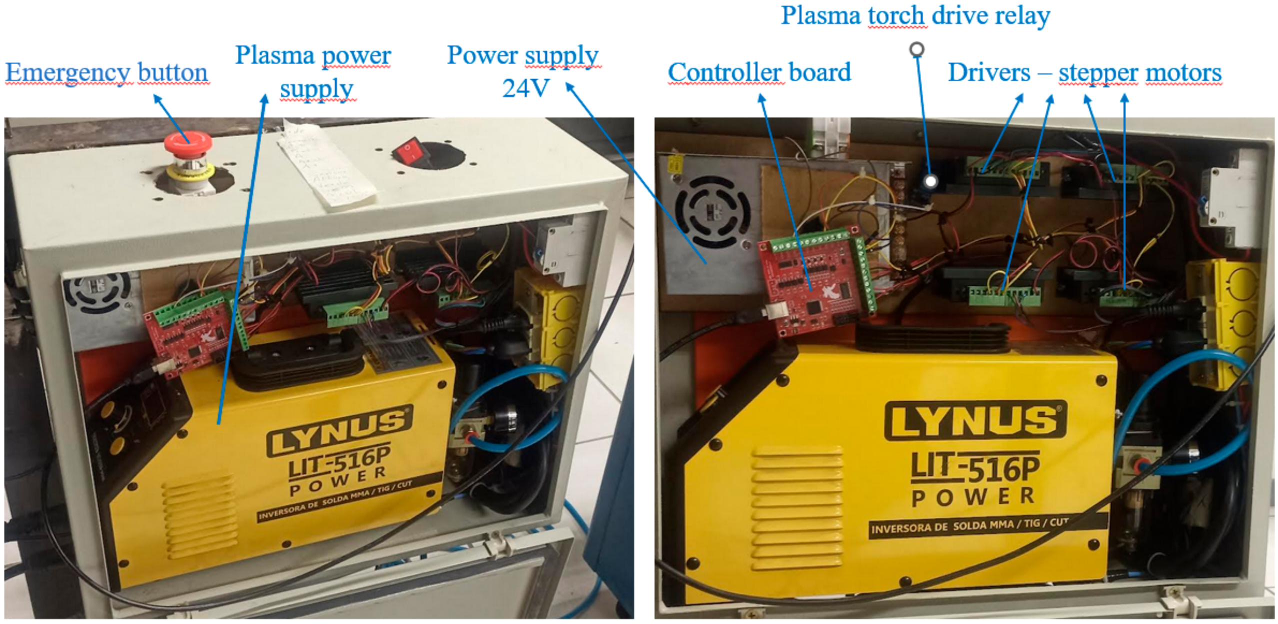
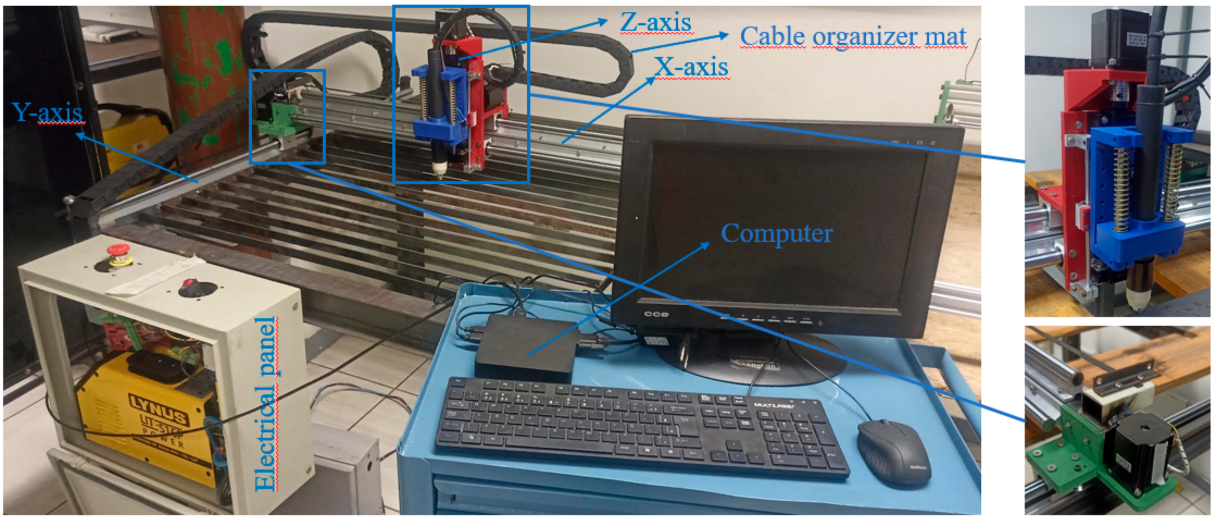


Figure 7. Prototype plasma cutting CNC



3.4 Movement tests and CNC calibration

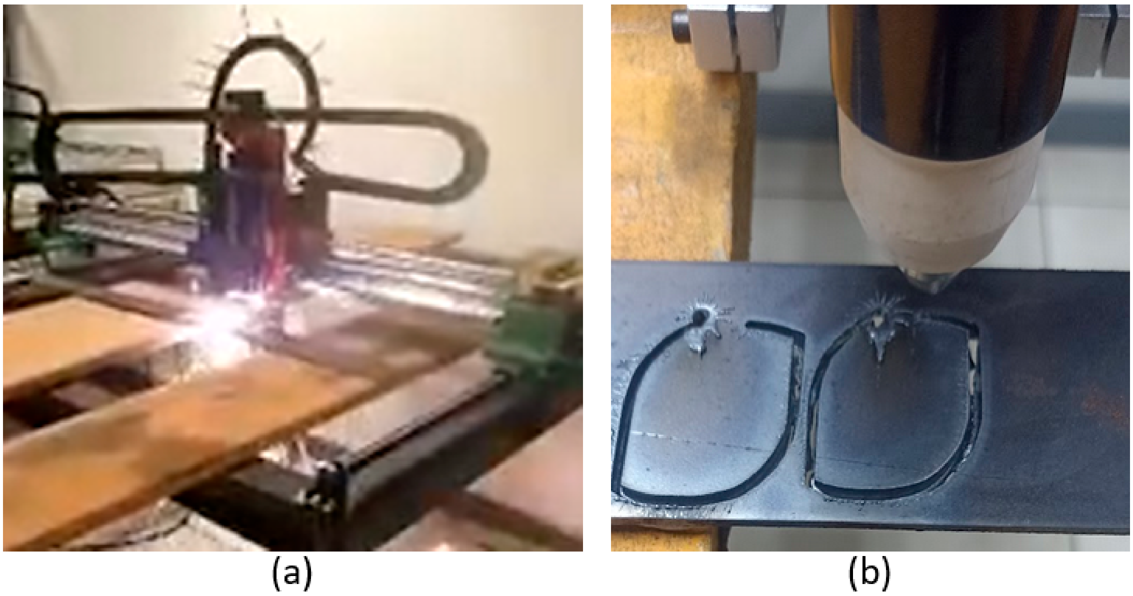
The plasma CNC movement tests began by checking the ability to move the axes via the computer keyboard. In this initial phase, inconsistencies were identified between the displacements requested in the software and what actually occurred in the CNC. Adjustments had to be made to the displacements to correct this discrepancy. To do this, each axis (X, Y and Z) was measured individually, comparing the actual displacement with the value requested in the software.

Unwanted vibrations were also identified when moving the axes. To solve this problem, adjustments were made to the acceleration and speed settings of the motors responsible for moving these axes. In addition, there was a need to tighten the belt that transmitted the movement and ensure proper lubrication of the linear guides. These actions were fundamental to minimizing vibrations and ensuring smooth movement of the X and Y axes. The acceleration and speed adjustments provided a better dynamic response from the CNC, while the tightening of the belt and proper lubrication helped to reduce friction and wear during movement.

3.5 CNC plasma cutting tests

Figure 8(a) shows the CNC in action, executing the cutting program on a 3 mm sheet of metal. However, in Figure 8(b), it can be seen that the cut did not correspond to the desired shape, presenting a distinct design instead of a circle. This indicates the need to make adjustments to the axis movements to ensure the accuracy and correct shape of the cut. In addition, it is clear that adjustments to the parameters of the cutting process are also necessary, such as the intensity of the electric current, the gas flow rate, the cutting speed and the appropriate distance from the torch to the workpiece. These adjustments are essential to achieve a complete, quality cut in the sheet metal. The plasma cutting tests revealed points that need to be refined and optimized to obtain the desired results, which will be addressed in the next stages of the CNC plasma development. In the next stages, optimization of axis movements and sheet metal cutting will be carried out.

Figure 8. (a) Plasma CNC in operation and (b) initial cut with the CNC



4 Conclusions

In summary, a plasma cutting CNC was designed and built for teaching purposes. However, some adjustments to the axis movements and process parameters are necessary to optimize plasma cutting with the equipment. In addition, the electrical panel needs to be improved, seeking a more efficient organization of the wires and positioning of the electronic components. So far, the safety systems, such as the emergency button, limit switch and circuit breaker, have not yet been implemented, but will be incorporated into the ongoing project. In addition, tests for teaching purposes are also planned to be developed in subsequent stages. The plasma cutting CNC project shows great educational potential, but requires continued efforts to improve and implement safety measures to ensure its full operation and the safety of users.

Safety systems must also be implemented in the CNC, i.e. an emergency button and end-of-travel sensors must be added to the device.

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