REGIONAL UNIVERSITY OF BLUMENAU

CENTER FOR EXACT AND NATURAL SCIENCES

COURSE IN INFORMATION SYSTEMS – BACHELOR'S DEGREE

BUILDING A LOW-COST 3D PRINTER

JONAS FERNANDO SCHUH

BLUMENAU
2024

JONAS FERNANDO SCHUH

BUILDING A LOW-COST 3D PRINTER

Final Paper presented to the undergraduate course in Information Systems of the Center for Exact and Natural Sciences of the Regional University of Blumenau as a partial requirement for obtaining the degree of Bachelor in Information Systems.

Prof. Miguel Alexandre Wisintainer, Master – Advisor

Prof. Cesar Ricardo Câmara da Silva, Master – Supervisor/Mentor

BLUMENAU
2024

This page must be replaced by the signature sheet delivered to the Board.

Scan the sheet and paste it here for the delivery of the final version of the TCC.

Warning: do not exceed the margins!

SUMMARY

This work presents the construction of a low-cost 3D printer. The main objective is to implement the assembly of the solution using low-cost parts, with open source hardware and software. The initial idea was to make a laser engraver based on a prototype of a Computer Numerical Control (CNC) router, but for safety reasons due to laser beam emission, it was decided to build a 3D printer. The prototype consists of a physical structure of recycled wood, low-cost mechanical structure and hardware based on the Arduino Mega 2560 and Kit Ramps 1.4 boards. The methodology consisted of bibliographic reference and was divided into mechanical, electronic and logical parts, until the prototype was functional. Much of the time of the project was used for testing and fine-tuning the prototype. All stages of the process were extensively documented in a sequential manner and detailed by means of technical drawings in three dimensions. In the results section, various types and techniques of 3D printing are exposed with their results commented and evidenced. This prototype has a differential of the Z axis having only one stepper motor to perform the movement that promotes reduction in cost, weight and complexity. Finally, the results obtained through the tests carried out demonstrate that the work developed achieved its objectives.

Keywords: 3D Printing, CNC, Arduino, Ramps, Low Cost.

ABSTRACT

This work presents the construction of a low-cost 3D printer. The main objective is to implement the assembly of the solution using low-cost parts, with open-source hardware and software. The initial idea was to make a laser engraver based on a prototype of a Computer Numerical Control (CNC) router, but for safety reasons due to laser beam emission, it was decided to build a 3D printer. The prototype consists of a physical structure made of recycled wood, a low-cost mechanical structure and hardware based on Arduino Mega 2560 boards and Ramps 1.4 Kit. The methodology consisted of bibliographical references and was divided into mechanical, electronic and logical parts, until the prototype was functional. Much of the project time was used for testing and fine-tuning the prototype. All stages of the process were extensively documented sequentially and detailed using three-dimensional technical drawings. In the results section, various types and techniques of 3D printing are exposed with their results commented and highlighted. This prototype has a Z axis differential and only one stepper motor to carry out the movement, which promotes cost, weight and complexity reduction. Finally, the results obtained through the tests carried out demonstrate that the work developed achieved its objectives.

Key-words: 3D Printing, CNC, Arduino, Ramps, Low Cost, RepRap.

LIST OF FIGURES

LIST OF CHARTS

LIST OF ABBREVIATIONS AND ACRONYMS

2D – Two dimensions

3D – Three dimensions

A – Ampere – Unit of electric current

ABS – Acrilonitrilo-Butadieno-Estireno

BPS – Baud Rate per Second

CNC – Computer Numerical Control

DIY – Do It Yourself

EEPROM – Electrically-Erasable Programmable Read-Only Memory

FFF – Manufacture of Cast Filaments

IDE – Integrated Development Environment

LCD – Liquid Crystal Display

LED – Light-Emiting Diode

MDF – Medium Density Fiberboard

MM – Millimeters

PET – Polyethylene terephthalate

PID – Proportional, Integral and Derivative

PLA – Poly Lactic Acid

RF – Functional Requirement

RNF – Non-Functional Requirement

Final Paper – Course Completion Work

USB – Universal Serial Bus

V – Volts

VREF – Voltage Reference

SUMMARY

1 INTRODUCTION

The possibility of creating objects in 3D, by means of a printer, is a revolutionary innovation, as it enables the way to transform the way of producing objects, from small household utensils to large industrial components (Silva; Silva, 2023). However, Silva and Silva (2023) comment that despite this potential, one of the main obstacles preventing the large-scale adoption of 3D printing is its high cost.

In view of this premise, with the growth and use of this technology, as well as Celerino *et al.* (2022) describe in their work, the challenge of building a 3D printer is created, with recyclable parts of used devices and electronic kits that are easily found in commerce, and it is possible to mention the *RepRap* and Arduino boards, which use codes that are developed and made available by collaborators from all over the world.

The acronym *Do It Yourself* (DIY), which translates to do-it-yourself, is highlighted in the media and on high-visibility sites such as YouTube, Instagram, and Google. This dissemination of knowledge has encouraged many to learn and assemble their own 3D printer through this collaborative scenario (Celerino *et al*. 2022).

The year 2005 was probably the most important year in the history of modern 3D printing, due to the fact that it was the year of the creation of the *RepRap* project, by Adrian Bowyer at the University of Bath, England (Prusa; Stritesky; Bach, 2020). Since its inception, it has been created to be open source, which is understood that all coding is publicly available. Thanks to *RepRap* it is possible to create low-cost 3D printers (Prusa; Stritesky; Bach, 2020).

In this sense, this research arises with the purpose of developing a prototype of a low-cost 3D printer. The construction proposal consists of the use of scrap metal, recyclable materials and electronic kits, as well as joinery components in order to reduce the cost. This printer can be used to reproduce items, in order to assist in studies in a more didactic way, in addition to stimulating creativity.

In view of the exposed scenario, this work aims to develop a prototype of a 3D printer that uses the main concepts described here, such as the use of recyclable and low-cost materials. This solution is a 3D printer with a wooden structure, slides, recycled motors that is capable of transforming 3D models into physical parts.

1.1 OBJECTIVES

The main objective of this work is to assemble a 3D printer with low-cost materials, using the Arduino microcontroller, Kit Ramps and make it functional.

The specific objectives are:

a) assembly of the mechanical part and the electronic part making the printer functional;
b) evaluate whether the printer achieves acceptable accuracy. If you want to print a 20 millimeter calibration cube to measure the accuracy of the equipment.

1.2 STRUCTURE

This work is divided into four chapters. The first chapter presents the introduction and objectives of the work. The second chapter deals with the theoretical foundation, explaining the main concepts and techniques used in the work. The third chapter contemplates the development of the prototype, where the architecture of the work is described, through technical drawings, details of the implementation and the results obtained. Finally, the fourth chapter presents the conclusions, as well as suggestions for future work.

2 THEORETICAL FOUNDATION

This chapter is organized into two sections. Section 2.1 comments on the literature review and section 2.2 presents the related works.

2.1 LITERATURE REVIEW

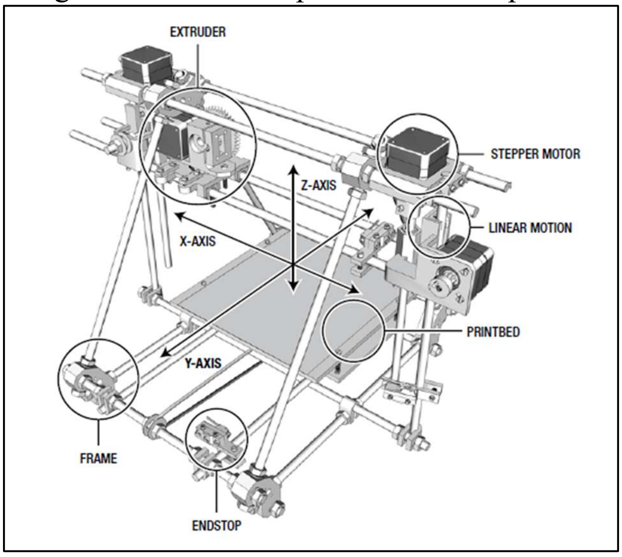
In this section, the topics of the literature review will be presented. The selection criterion was based on the subjects that make up the title of this project "Low-cost 3D printer". In subsection 2.1.1, it was decided to contextualize the concept of 3D printing and finally, in subsection 2.1.2, it was chosen to contextualize the *Marlin* firmware that will manage the data source.

2.1.1 3D Printing

3D printing, as Prusa, Stritesky, and Bach (2020) describe in their work, is understood as a sequence of automated manufacturing processes that occurs additively, that is, in sequential layers, which generate a physical model based on a digital object in the format of three dimensions. Currently there are several technologies for this type of printing and Cast Filament Manufacturing (FFF) stands out as the simplest. It consists of an object created by sequential layers, composed of the controlled melting of a plastic thread (Prusa; Stritesky; Bach, 2020).

There are several models of 3D printers, but they all share similarities in the basic structure of the components, as Evans (2012) shows in his work, as shown in Figure Figure 1 - Basic components of a 3D printer, of the main components, such as X, Y, Z axes, extruder, hot printing bed and limit switches.

Figure 1 - Basic components of a 3D printer



Font: Evans (2012).

By author's translation, as illustrated in Figure 1 - Basic components of a 3D printer, the X axis of movement is responsible for width, Z axis is responsible for height, and the Y axis is responsible for depth. *EndStop* is understood as the end-of-course controls and *Printbed,* also in English, is understood as a print bed or heated bed.

3D printers have been available for years, but only recently have they been available in the purchasing power range of most home users. Horne and Hausman, (2017) comment in their work that this technology has the potential to cause a significant impact on average consumers, as it will enable many innovations, through the creation of a very wide range of materials in their various combinations and formats.

2.1.2 Marlin Firmware

Celerino *et al*. (2022) state that firmware is low-level software that aims to communicate directly with hardware. Among other firmwares available on the market, we can mention the *Marlin* firmware, which works on ATMega2560 microcontrollers and is widely used in 3D printers (Celerino *et al.* 2022).

The Marlin *firmware* is an open source project, hosted on GitHub, owned and maintained by the Maker community, created in 2011 for *RepRap* (Zalm *et al.* 2011). Among its characteristics, excellent print quality and various configurations for all components of a 3D printer can be highlighted. Zucca and Machado (2019) comment in their work that for it to work on the built printer, it is mandatory to adjust the parameters and settings according to the particular characteristics of each project. One can cite as configuration the measurements of height, width, depth, sensors present, type of plate used, calibration of distances traveled in millimeters, number of revolutions in the motors according to the thickness of the gears. In addition to calibration, this software helps to check the temperatures and sizing of the object in the *hotbed*, which is understood as a hot bed (Zucca and Machado, 2019).

Silva *et al.* (2023) highlight in their work that *Marlin* also performs the interpretation of G-Code commands, a programming language that controls the direction of the precise movements of the 3D printer, resulting in the conversion of control signals to the motors, heaters, and other components of the printer.

2.2 RELATED

In this subsection, the works listed in Chart 1 will be presented. Research was carried out on several sites, including Google, CAPES Journal Portal, Google Scholar and the TCC research portal of the Department of Systems and Computing of FURB.

The data source selected for the search for works related to the proposed and their respective bibliographic sources was the Google Scholar website, with the filter "Since 2019", keywords "low-cost 3D printer", in which the tool returned approximately 5,770 results. A search was also carried out on the CAPES Journal Portal, to which only 15 online resources were returned, but no record relevant to the proposed work was found.

Six related works were selected for the reason that there was affinity with the project and after a refinement, three most relevant works were chosen that have characteristics more similar to the proposed work. The first selected work is "The DIY Philosophy: repurposing electronic scrap for the construction of a low-cost 3D printer", (Level *et al.* 2022). The second selected work was the "Development of a low-cost 3D printer for prototyping parts for rural areas" by (Zucca; Machado, 2019) and finally "Construction of a low-cost 3D printer with alternative materials", developed by (Batista, 2021).

Chart 1 - Synthesis of the selected related works

Subject	Filter	Reference
The DIY Philosophy: repurposing electronic scrap for low-cost 3D printer construction	low-cost 3D printer	Level *et al.* (2022)
Development of a low-cost 3D printer for prototyping parts for rural areas	low-cost 3D printer	Zucca and Machado (2019)
Building a low-cost 3D printer with alternative materials	low-cost 3D printer	Baptist (2021)

Source: prepared by the author (2023).

By considering the premises described, the theoretical bases relevant to the subject were selected to solve the proposed problem. Among the selected related works, all have in common the fact that the printers were assembled by the students, but each one with its own particularity and with different techniques and models, different from the proposed project. In addition, the three related works aimed to reduce costs and reuse of waste parts.

The selection and refinement criteria used for the selection of the works related to this project were in the work of Level *et al.* (2022), the question that the 3D printer was built from reused parts of electronic waste, with the idea of reusing used parts, transforming them back into something useful. The work by Zucca and Machado (2019) was selected for the reason that this project was not funded and that various methods were used to reduce expenses as much as possible. It can also be mentioned that the Arduino Mega 2560 was used, the same one that will be used in this work, in addition to having the other characteristics, among them, pedagogical connotation, approach to difficulties faced during the realization of the project, such as mechanical problems and heating of the electronic components. Finally, the third selected work was that of Batista (2021), who also focused on the use of low-cost or disposable alternative materials and has a focus on the use of firmware and free software made available for free.

2.2.1 The DIY Philosophy: repurposing electronic scrap for low-cost 3D printer construction

Developed by Level *et al.* (2022), the article presents the creation of a 3D printer aimed at the reuse of electronic waste, promoting sustainability, reuse, and the issue of *the Do It Yourself* (DIY) philosophy, which translated from English, is understood as do-it-yourself.

The physical structure of the prototype was built with leftover MDF wood, nuts, bolts and washers. In the mechanical part, smooth and threaded shafts, extruder unit, NEMA17 stepper motors and its electronic part composed of a controller unit based on the Arduino board, with power controllers with voltage and current regulation for each motor, LCD panel with the objective of displaying process and temperature information. (Level *et al.* 2022).

The software used to operate the prototype was the GRBL Master library, through the Arduino UNO platform. Level *et al.* (2022) comments that through this library, it was possible to use the open source software GRBL to control the X, Y and Z axes, but the three motors were defective and had to be replaced by new motors, purchased for a total of R$ 223.90 between product and shipping. The extruder also had to be purchased in the amount of R$ 180.00, totaling a cost of R$ 403.90.

After the prototype was operational, Level *et al.* (2022) expose the results obtained in the experiment, where a performance comparison was carried out between the prototype developed by the authors in relation to a commercial printer. In this experiment, the following parameters were analyzed: resolution, printing time, fillings (%), errors and waste of printed material (%). The results obtained in general demonstrated the potential of producing a high-tech printer with scrap material, showing that it is possible to make reuse a real alternative so that old equipment can have its usefulness recreated. (Level *et al.* 2022).

Level *et al.* (2022) concluded that all the objectives of their work were achieved. The results obtained showed that it is possible to create a 3D printer with a low budget and satisfactory results. They also emphasize the use of sustainable practices that sought to contribute to socioeconomic development and environmental preservation.

2.2.2 Development of a low-cost 3D printer for prototyping parts for rural areas

Zucca and Machado (2019) developed a low-cost 3D printer with the aim of proposing its use in the development of parts, tools, or prototypes in the agricultural environment. The specific objectives of the work consist of assembling a low-cost 3D printer capable of printing a varied number of objects, comparing the print quality with parts printed by a similar printer sold in the market, in addition to evaluating the cost of assembly and imported parts in relation to printers sold in Brazil (Zucca; Machado, 2019).

The prototype developed on site used Arduino Mega 2560 boards and Ramps (RepRap Contributors, 2024) version 1.4, extruder kit and heated board purchased. The X and Y axis motors were reused from old word printers and their set of linear guides and belts. The assembly was carried out in three parts, the first being the structural and mechanical part, then the electrical part and finally the installation of the software and firmware used in the 3D printer (Zucca; Machado, 2019).

During the tests, Zucca and Machado (2019) compared a part printed by the constructed printer with the result of a part printed by a *Prusa* i3 printer already tested and certified and concluded that the results were identical, that is, a low-cost 3D printer proved to be a quality alternative in relation to commercial printers with a higher value. Also to demonstrate the application of the printer manufactured in rural areas, several gears of adjustable size were printed to be used in poultry sheds, as well as supports for vegetable gardens. The total cost of the project was estimated at R$ 1126.10. They also concluded that if the components were purchased directly in China, the value would be estimated at R$ 586.29, that is, the project would fall by practically half the price.

Zucca and Machado (2019) achieved all the objectives in their work. They concluded that it is possible to build a *RepRap 3D printer* for use in low-cost rural areas. They also state that the 3D RepRap technology made it possible to reduce the cost of practically half the amount that would be invested in the acquisition of a 3D printer sold in the national market. In future studies, they recommend performing resistance tests on the parts produced by the low-cost 3D printer, in order to simulate real efforts that occur during the production process when replacing broken parts with parts produced using 3D printing.

2.2.3 Building a low-cost 3D printer with alternative materials

Batista (2021) developed a low-cost 3D printer and largely used materials from disposal and electronic waste. In the structural part, parts taken from old dot matrix printers and other obsolete equipment were used, such as plastic tubes, aluminum angles, leftover MDF, threaded bars, screws and clamps. In the electrical part, a switching power supply was reused, stepper motors taken from printers fora de uso e alguns componentes eletrônicos. As demais peças used in the assembly were acquired through an electronic kit, containing the Arduino UNO and CNC Shield boards and an extruder nozzle.

The firmware used in this experiment was *Teacup*, which is free and open source. Batista (2021) also states that although *Teacup* is very useful because it is simple, it is being replaced with advantages by the *Marlin* framework, but *Marlin* is not compatible with Arduino UNO, which justified the choice of *Teacup*.

Batista (2021) concludes in his work that the construction of a 3D printer involves several areas of knowledge, including structural and electrical assembly, and the use of computer software. That is why it requires organized research, discipline and patience in obtaining this knowledge to achieve the expected result. He also comments that during the assembly and use of the proposed printer there were several difficulties. One of them was the excess of clearance between the plastic bushings and linear guides, which made it difficult to achieve the necessary precision, perceived already in the first impressions.

Another perceived problem, according to Batista (2021) that affected the accuracy of the X and Y axes was the gap between the nut, which performed the function of a nut and threaded bar. The resolution of this situation occurred with the fixation of the motors through adaptation with hot glue. Batista (2021) also emphasizes that he realized that there is no accurate control for the speed of entry into the extruder filament. He also mentioned that the non-use of the heated table denoted the detachment of several parts of the table, resulting in loss of time and material used.

Batista (2021) also comments that end-of-course sensors were not used in this prototype, with the aim of simplifying the project. Finally, it was concluded that despite the purposeful limitations imposed, the device proved to be functional and useful (Batista, 2021).

3 PROTOTYPE DEVELOPMENT

This chapter demonstrates the steps of prototype development. In section 3.1, the main requirements are presented. Section 3.2 presents the specification and technical drawing. Section 3.3 describes the implementation in detail. Finally, section 3.4 demonstrates the results of the prototype's tests, suggestions, and improvements.

3.1 REQUIREMENTS

The prototype should:

a) allow the user to print a 20 millimeter calibration cube (FR);
b) allow the user to evaluate whether the prototype generates 3D objects with acceptable accuracy (FR);
c) allow the user to 3D print parts of the Furbot (FR) project;
d) be assembled with low-cost parts (Non-functional requirement – NFR);
e) use open source firmware (NFR);
f) operate with open source software (NFR);
g) generally promote the reuse of electronic waste for something useful again (NFR);
h) use recycled components from other electronic devices (NFR);
i) use recycled wood (NFR);
j) have the ability to operate for more than 10 hours without failure (NFR);
k) usar o Framework Marlin (NFR);
l) use open source hardware (NFR).

3.2 SPECIFICATION AND TECHNICAL DRAWING

This section presents the specification of the prototype through a bibliographic model, the structure of an old prototype of a CNC plotter, the creation of a 3D model by reverse engineering the design of the printer, and an electrical schematic of connecting the components. The tools used were the SketchUp and Microsoft Paint applications.

3.2.1 Printer design

The initial idea for the development of the prototype was through bibliographic research in foreign books, due to the fact that there is little bibliography on this subject in the Portuguese language. Research in academic papers and scientific articles on the subject was also taken into account.

The model is a Prusa-type 3D printer, as shown in Figure 1, which served as a basis for glimpsing the main components of a 3D printer and its mechanical and electronic structure. The selection was due to the fact that the mechanical parts operate in the same way as the prototype of the old CNC router, in **Erro! Autoreferência de indicador não válida.**, as an example, the Y-axis moves at the base back and forth. There are other models of printing structure, where the Y axis is static and the movement takes place through the other axes.

3.2.2 2D CNC Router Prototype

The basis of this project began with the prototype of a 2D CNC router completed in 2018, as shown in Figure 2, developed as a hobby by the author and used recycled parts and a CNC Shield controller board, controlled by an Arduino UNO board. One motivation for using it was the use of parts and structure, such as stepper motors, telescopic slides and recycled wood structure.

Figure 2 - CNC router before being turned into a 3D printer

Source: prepared by the author (2023).

One can also mention the issue of square and angles, which in the course of the study proved to be fundamental for the 3D printer to work properly. As an example, as shown in The model is a Prusa-type 3D printer, as shown in Figure 1, which served as a basis for glimpsing the main components of a 3D printer and its mechanical and electronic structure. The selection was due to the fact that the mechanical parts operate in the same way as the prototype of the old CNC router, in **Erro! Autoreferência de indicador não válida.**, as an example, the Y-axis moves at the base back and forth. There are other models of printing structure, where the Y axis is static and the movement takes place through the other axes.

3.2.3 2D CNC Router Prototype

The basis of this project began with the prototype of a 2D CNC router completed in 2018, as shown in Figure 2, developed as a hobby by the author and used recycled parts and a CNC Shield controller board, controlled by an Arduino UNO board. One motivation for using it was the use of parts and structure, such as stepper motors, telescopic slides and recycled wood structure.

The decision to make a 3D printer arose from the suggestion made by the future advisor at the time, professor of electronics at FURB, Prof. Ms. Miguel Alexandre Wisintainer (Wisintainer, 2014). The author's suggestion was to make a laser engraver, since the entire CNC structure would work only with the X and Y axes, that is, in 2D, but after studies, it was concluded that the 3D printer was the best option, due to the fact that the laser is dangerous due to the ultraviolet rays that can cause serious vision problems during tests.

During this period, not all the known problems in this work were known. As an example cited in related works, it is possible to verify mechanical problems, heating, vibration, oscillation, lack of precision that were adjusted during the testing phase.

3.2.4 3D Printer Computer Laboratory FURB Campus I

During the author's undergraduate period in the Information Systems course at the Regional University of Blumenau Foundation (FURB), a 3D printer was observed in the computer lab located on the fourth floor of block I of this institution. As illustrated in Figure 3, details of the printer's components, such as mechanical structure and some electronic components, can be observed.

Figure 3 - Detail of the FURB Campus 1 laboratory printer

Source: prepared by the author (2023).

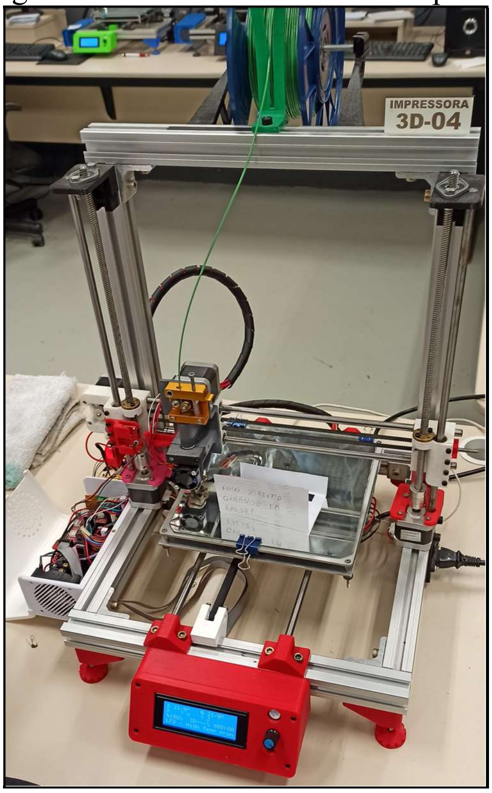
The author observes that the structure of this printer has a different mechanical functioning from the *Prusa* model found in the bibliography. This model is closed and ideal for printing with ABS plastic and has a fixed heated table that goes up and down at its base. It is a commercial printer, with a brand and proprietary technology. 3D printing should start with the base at the top and as the printing layers are made, the base will go down until the print job is finished. It is also observed that this commercial model uses spindles for sliding the printing carriages and the traction of the axles occurs by means of belts.

3.2.5 3D Printer Electrical Engineering Laboratory - FURB Campus II

During the project phase of this academic work, a visit was made to the Electrical Engineering laboratory of FURB - Campus II, to invite the future mentor of the project, professor of the Electrical Engineering Course, Prof. Ms. Cesar Ricardo Câmara da Silva (Silva, 2017).

During the visit to the laboratory premises, as shown in Figure 4, several 3D printers can be seen in operation, as well as a large CNC Laser router.

Figure 4 - FURB 3D Printer - Campus II



Source: prepared by the author (2023).

In conversation with the project's mentor, the author commented on the conception of the project to create a low-cost 3D printer and asked questions about the basic structure of a 3D printer, as well as some technical details, such as the use of a solid-state relay as an alternative source of energy for the heated table, as a palliative measure, the use of a heated table connection directly on the Ramps plate (RepRap Contributors, 2024). The use of extra-strong hair fixing spray was also observed, which is used to assist in the fixation of 3D printed objects in the printers.

The author observes, in Figure 4, that the structure of this printer is similar to the 3D *Prusa* model, which has a structure similar to the idea of adapting the CNC router. In this architectural model, the heated table is located on the Y-axis and moves back and forth with the aid of belts.

3.2.6 Reverse engineering the built prototype

The construction of the technical drawing of the prototype structure in 3D took place after the prototype was functional. The beginning of the creation of the drawings was carried out with the open source tool FreeCad (FreeCad Team, 2024) which is a tool for parametric drawings in 3D. Online courses were held to learn how to use the application, but it was found that it is very laborious to use for illustration purposes. The point of greatest difficulty was the issue that all the angles and arcs of the 2D object must be drawn, interconnected to then generate a 3D model. The construction of the model occurs incrementally in several layers of small 3D objects until the piece is finished.

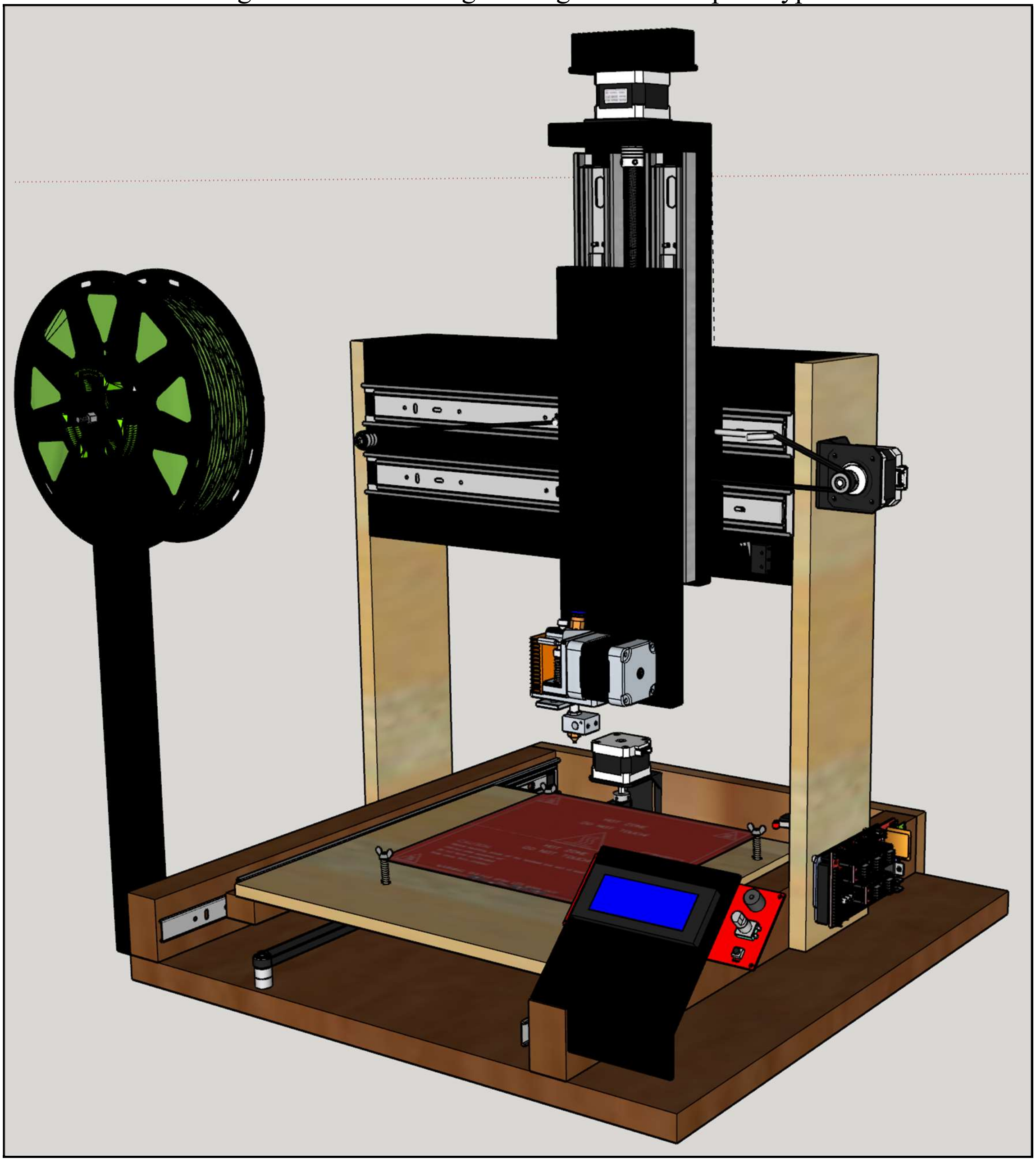
In view of this situation, research was carried out on another tool more suitable for the purposes of building the illustrations and the most appropriate solution was the SketchUp tool (Trimble Inc, 2023). This tool has paid and subscription versions, but the online version was made available for free.

SketchUp (Trimble Inc, 2023) has a different methodology for using 3D objects. It stands out for its simplicity of use because it does not need to connect the angles and arcs. The drawing is done in 2D and after the geometric shape is created, it is automatically transformed into 3D.

The 3D models of the printer parts such as stepper motor, telescopic slides, screws, extruder were used from the Warehouse 3D model repository (Trimble Inc, 2024). Some 3D models of parts that were not found in this repository were designed by the author, as an example we can mention the support for the LCD display and traction plates of the threaded bar used in the Z axis.

The prototype was built incrementally, as shown in Figure 5, described step by step in section 3.3. After being completed, reverse engineering was carried out using 3D models in order to facilitate the understanding of what was built in all its stages.

Figure 5 - Reverse engineering of the built prototype



Source: prepared by the author (2024).

In In view of this situation, research was carried out on another tool more suitable for the purposes of building the illustrations and the most appropriate solution was the SketchUp tool (Trimble Inc, 2023). This tool has paid and subscription versions, but the online version was made available for free.

SketchUp (Trimble Inc, 2023) has a different methodology for using 3D objects. It stands out for its simplicity of use because it does not need to connect the angles and arcs. The drawing is done in 2D and after the geometric shape is created, it is automatically transformed into 3D.

The 3D models of the printer parts such as stepper motor, telescopic slides, screws, extruder were used from the Warehouse 3D model repository (Trimble Inc, 2024). Some 3D models of parts that were not found in this repository were designed by the author, as an example we can mention the support for the LCD display and traction plates of the threaded bar used in the Z axis.

The prototype was built incrementally, as shown in Figure 5, described step by step in section 3.3. After being completed, reverse engineering was carried out using 3D models in order to facilitate the understanding of what was built in all its stages.

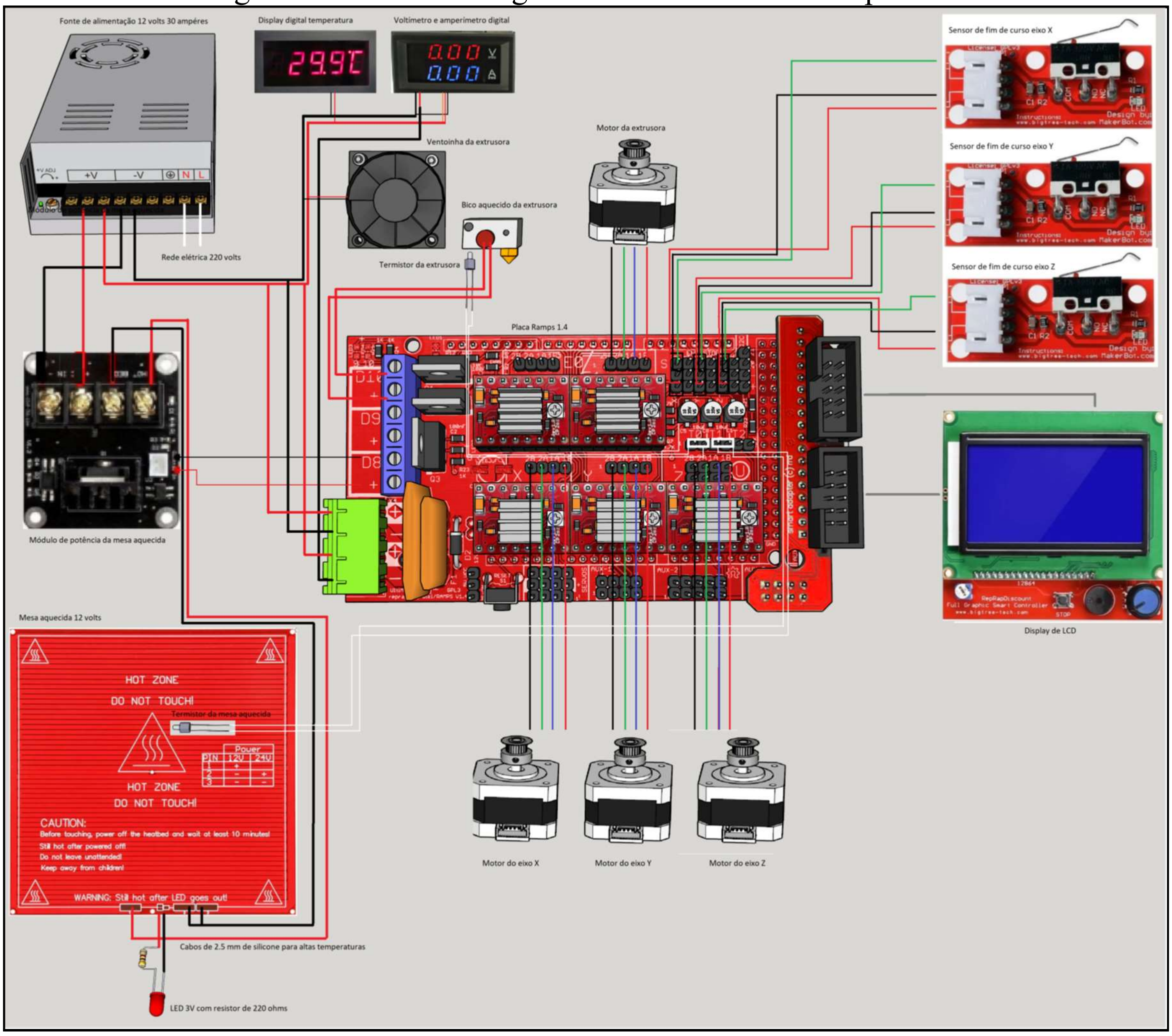
, you can see the 3D model of the prototype created, already functional and with all the final components.

3.2.7 Electrical schematic of 3D printer components

The connection of the electrical components of the prototype also occurred incrementally and its electrical scheme in the functional version is illustrated in Figure 6, elaborated by means of reverse engineering. The development in detail is described in section 3.3, but it can be stated that during the initial phase, some components were connected in isolation and as success was achieved, improvements were incorporated. Also in this phase there were several problems where the electrical scheme had to be changed and adapted.

Figure 6 shows the final version of the functional electrical schematic with all the components used, including sensors and actuators.

Figure 6 - Electrical diagram of the 3D Printer components



Source: prepared by the author (2024).

This technical illustration was created with the Microsoft Paint tool, and the 3D models of the components were imported from the SketchUp tool (Trimble Inc, 2023) and the 3D Warehouse repository (Trimble Inc, 2024).

3.3 IMPLEMENTATION

This section shows the breakdown of the implementation of the work. In section 3.3.1, the details of the purchase and construction of the prototype hardware are presented. Section 3.3.2 shows the techniques and tools used. Finally, section 3.3.3 details the installation and configuration of the electronic components, firmware, and software.

3.3.1 Prototype hardware construction

The construction of the physical part of the prototype took place incrementally. In a first stage, an in-depth bibliographic research of books, scientific articles, Course Completion Papers (TCC), found on platforms such as Google Scholar, among others, was carried out to support the initial idea about the construction of the prototype. From this study, a list of materials needed to assemble the prototype was prepared.

3.3.1.1 Purchase of parts

The initial parts used in the prototype were based on the structure of the CNC router and its components, as shown in Figure 7, in addition to the purchase of screws, electrical cables, drill bits, tools to measure level and square to measure angles.

Figure 7 - Purchase of parts

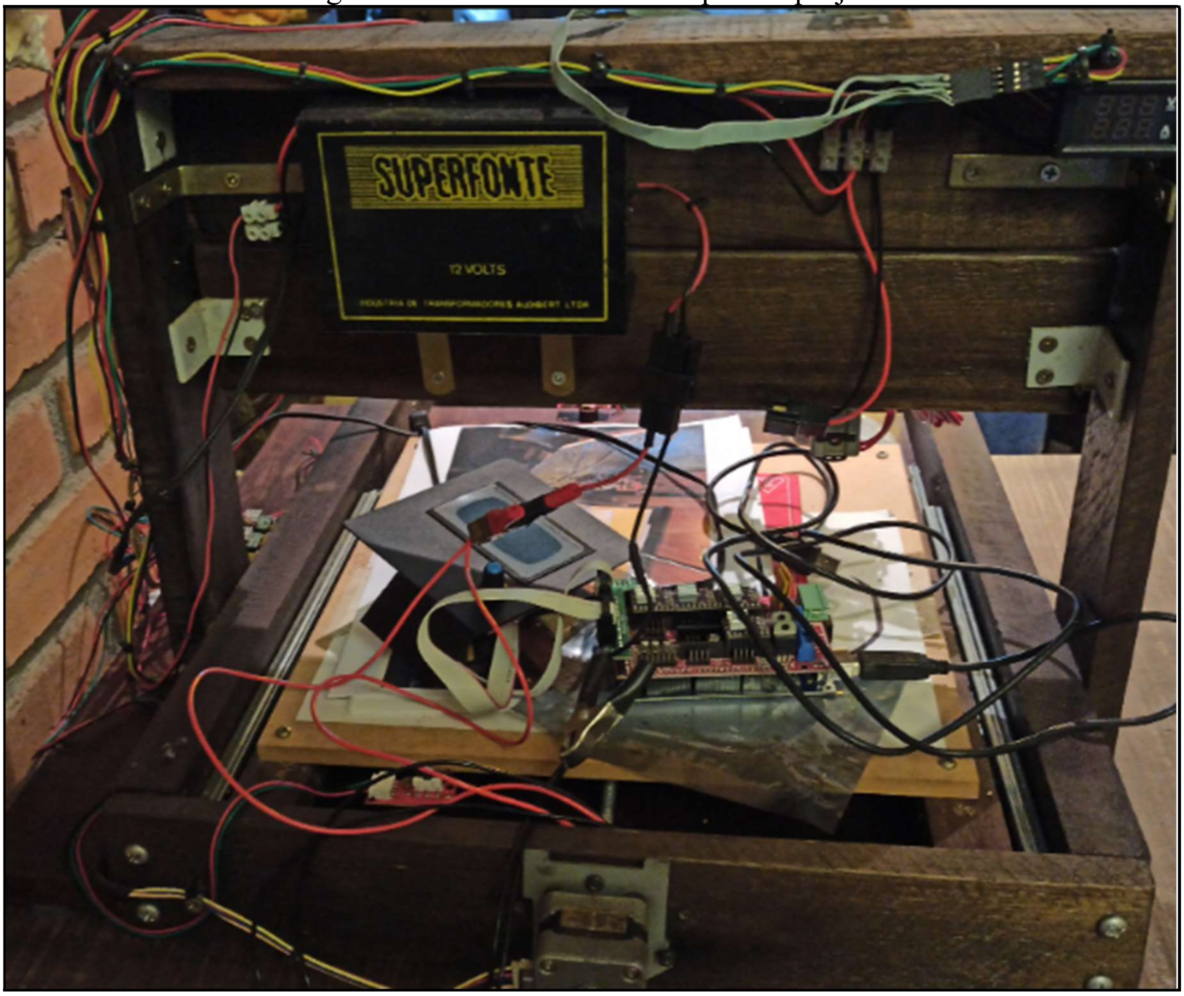
Source: prepared by the author (2023).

Some electronic components were imported from China, through the Aliexpress website, due to the fact that the price is more affordable than that found in Brazil. The components purchased were the Ramps 1.4 electronic kit for 3D printer which consists of a heated table model Mk2, Arduino Mega 2560 and Ramps 1.4 boards, five limit switches, two temperature sensors and an MK8 extruder complete with all power cables. The payment of the components was made through the Aliexpress website and the shipment arrived via mail in approximately three weeks at the plaintiff's residence.

It can be seen in that at that time the prototype still contained threaded feed bars for all axles, which were later replaced by timing belts, which increased the printing speed and facilitated maintenance.

The back of the initial prototype is illustrated in Figure 8 and contained a 12V power supply with transformer, with 70 watts of power, that is, 7 amps, which was also replaced by a 12V switching power supply and 30 amps, because the prototype built works with 12V and demands more energy, Because it is incorporated into the heated table that requires approximately 11 amps and the extruder about 2 amps.

Figure 8 - Rear view of the 3D printer project



Source: prepared by the author (2023).

It can also be observed that all the fittings of the wooden part were fixed by means of angles and the entire structure was sawn with a manual saw, without any concern for squares. These items were replaced in order to improve the alignment and finish of the new prototype.

The purchase list of the initial pieces, available in Chart 2, has values quoted at the time of preparation and acquisition of the items on the list, in October 2023. The components were obtained through donations by companies located in the city of Blumenau, Santa Catarina and by the author's personal collection.

The wooden structure was assembled with part of the structure of the old CNC, MDF scraps owned by the plaintiff and the recycling of pallets collected in the garbage of a civil construction site near the plaintiff's residence. The motors were removed from scrap metal from three Epson inkjet printers, which were donated by the company SOS Printers, located in the city of Blumenau, Santa Catarina.

Chart 2 – Parts purchase list

Material	**Quantity**	**Price** R$	**Origin**
Wood base 50x50cm	1	0,00	Recycling/Donation
Woods structure 7cmx35cm	6	0,00	Pallet recycling
Corrediça telescópica 30cm	2	31,64	Keunecke Hardware
Folding thick sheet 50mm	1	7,06	Keunecke Hardware
Bolts Steel 3.5 x 14mm	30	1,87	Keunecke Hardware
Threaded Bar 1/4 inch	2	4,98	Açopar
Nuts and fastener plates	3	10,00	Açopar
Welding of the nuts on the sheet metal	1	30,00	Ferreiro
Stepper Motors Epson 132 Columns Printer	2	0,00	SOS Printers Donation
Motores de passo impressora Epson Jato de Tinta	1	0,00	SOS Printers Donation
Cast iron 12v 7 amps	1	0,00	Personal donation
Voltage and Amperage Display Digital Temperature Viewer	1	20,34	Aliexpress
3D Printer Ramps 1.4 Kit, Arduino Mega 2560, Hotbed mk2b, LCD Display 12864, LCD Controller, A4988 Driver, 3 Mechanical Limit Switches with Cables	1	212,56	Aliexpress
3D Printer LCD Cover 12864 ender3	1	53,17	Aliexpress
Ramps-Mk8 Extruder with 0.4mm Nozzle Filament Kit for Motor, J-Head Extrusion, Hotend Head 1.75mm, 12v 40w	1	116,43	Aliexpress
0.7mm cables	10	25,00	Proesi Electronic Components
TOTAL		513,05	

Source: prepared by the author (2023).

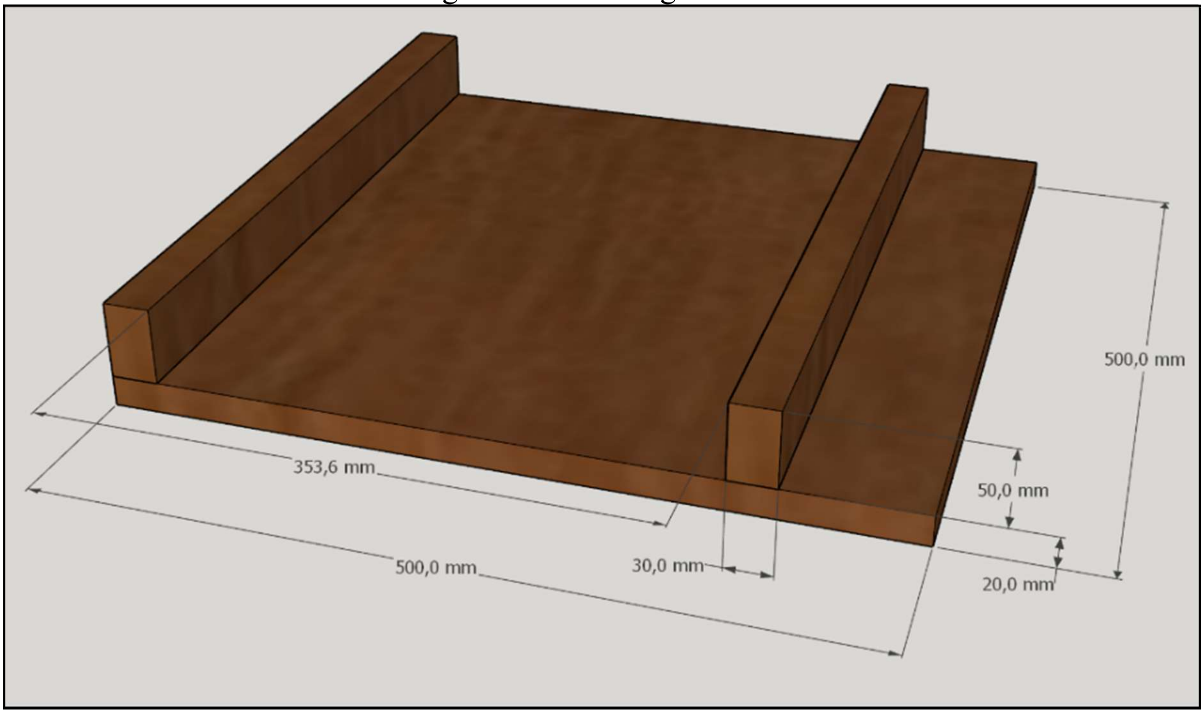
The plates, screws, telescopic slides, were acquired at the company Keunecke Ferragens, located at Telescopic slide 30cm in the city of Blumenau, Santa Catarina. The screws, nuts, washers, threaded bars were purchased from the Açopar company located in the city of Blumenau, Santa Catarina. The electrical cables used in the prototype were purchased from the company Proesi Electronic Components, located in the city of Blumenau, Santa Catarina. The acquisition of the electronic kits was carried out through the import of orders from China through the Aliexpress e-commerce site.

3.3.1.2 Assembly of the main physical structure

The assembly of the prototype began with the disassembly of the old CNC prototype, with the objective of reusing several parts, including the base, composed of a cinnamon wood sheet and two lower columns, as seen in Figure 9.

The towers of the initial prototype, with pallet wood, were replaced by reused MDF wood. The main reason was the lack of a 90-degree angle due to the cut with a manual saw and the fact that the woods had an irregular curvature, which would make it impossible to have the perfect angle and without variations for the printing course.

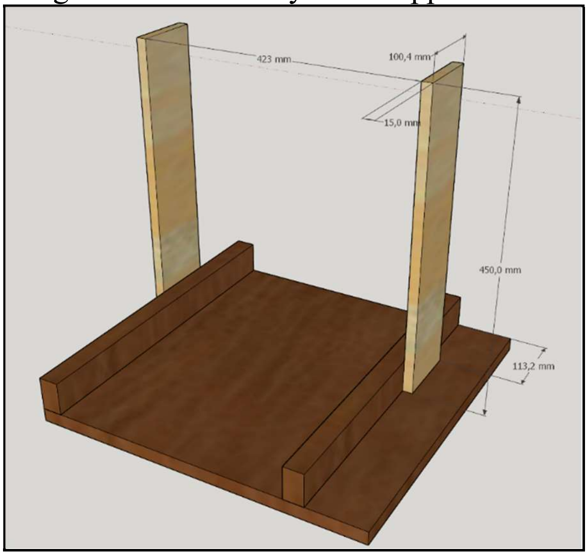
Figure 9 - Mounting the base



Source: prepared by the author (2024).

During implementation, these towers were assembled and disassembled three times, in different positions, until reaching an alignment compatible with the other components of the printer, such as the stroke of the heated bed positioned on the Y axis and with the initial position of the extruder. Also at this stage, the square and level tools were essential to correct angle variations during fixing. The wood used was 15 mm MDF, which was left over from the construction of the kitchen furniture in the plaintiff's apartment. The level of the table on which the printer was mounted was also measured, and the alignment of the towers occurred at the same level, as shown in Figure 10.

Figure 10 - Assembly of the upper towers



Source: prepared by the author (2024).

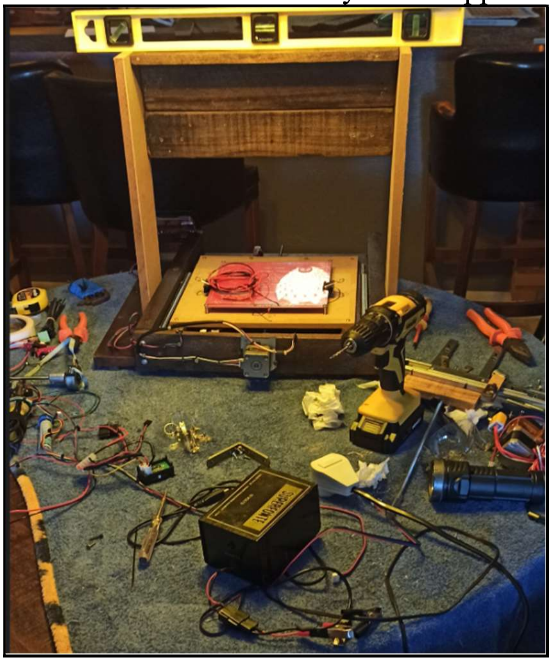
The woods were cut by a professional machine by the company Compensados Keunecke located in the city of Blumenau, Santa Catarina, where a perfect angle of 90 degrees is obtained. At this stage, several adjustments were made with the square until the perfect angle between the two columns and base was reached. The fixation was made by superb screws of 3.5 x 25 mm and the holes were made with a 2.5 mm drill. shows details of alignment 0 of the front part during the assembly of the upper towers.

Figure 11 - Front part of the assembly of the upper towers

Source: prepared by the author (2024).

During construction, a level ruler was used a lot, for the reason that the alignment of the printer must be 180 degrees from the base and 90 degrees each tower, as shown in Figure 11.

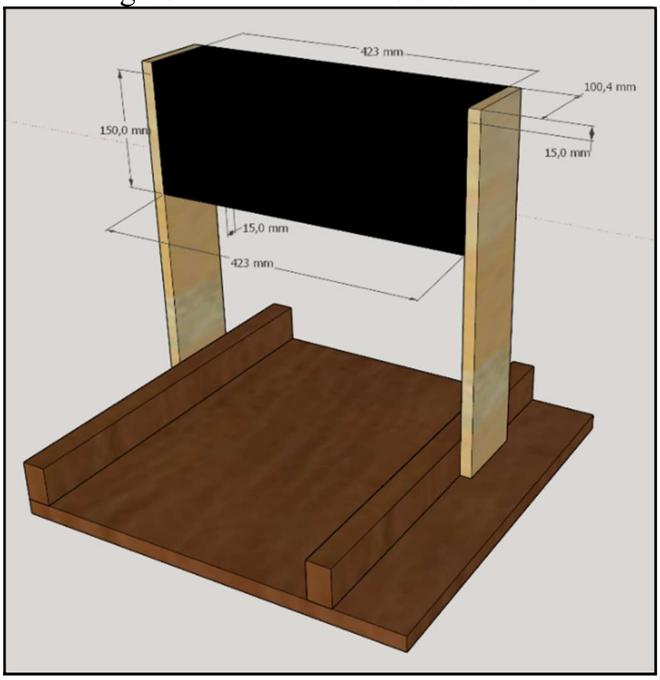
Figure 12 - Rear of the assembly of the upper towers



Source: prepared by the author (2024).

Figure Figure 12 shows that at this stage, pallet wood was still being used to join the upper towers, but later they were also replaced by MDF wood due to the fact that the pallet wood had irregular curvatures.

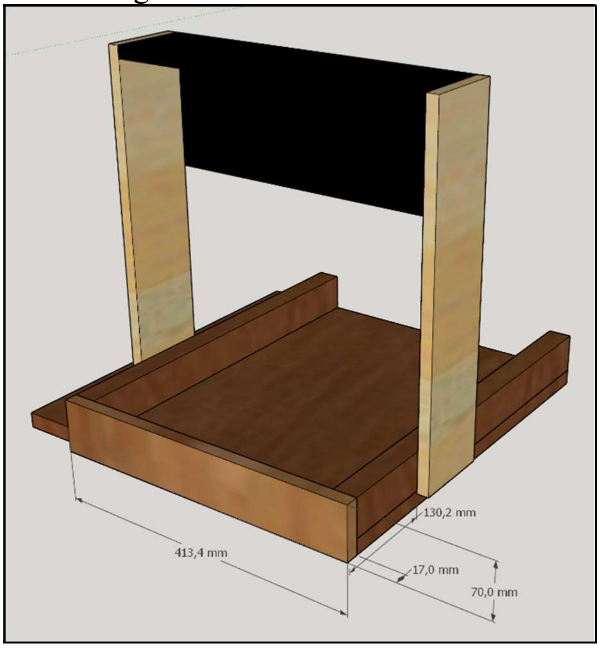
Figure 13 - MDF X-axis base - Front



Source: prepared by the author (2024).

The base of the X axis, as shown in Figure 13, was replaced by reused MDF wood, due to the square and angle of 90 degrees. Two plates that the plaintiff had in his residence were used. The cutting was also carried out by the company Compensados Keunecke located in the city of Blumenau, Santa Catarina with a professional cutting machine. The fixation was made by superb screws of 3.5 x 40 mm and the holes were made with a 2.5 mm drill bit.

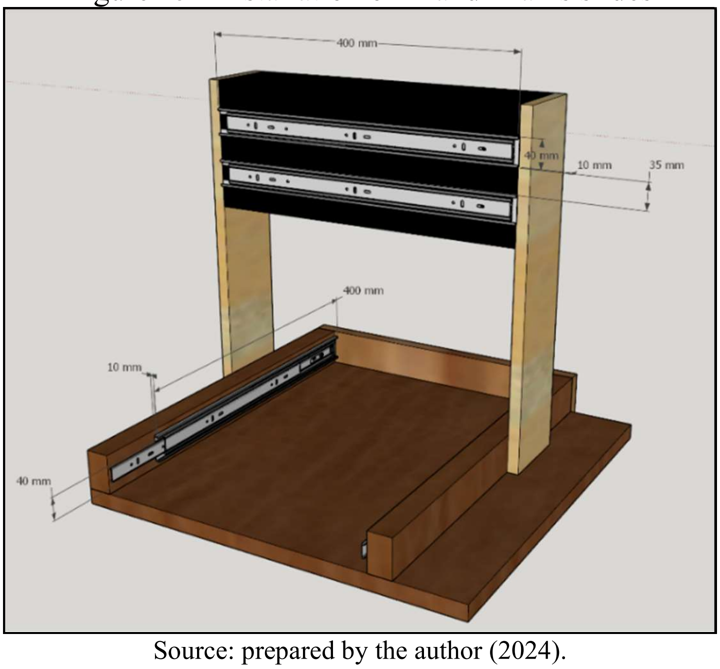
Figure 14 - Rear of the X-axis



Source: prepared by the author (2024).

The back of the X-axis base remained from the original design, as shown in Figure 14, being made of recycled pallet wood. The fixation was made by superb screws of 4 x 20 mm.

Figure 15 - Installation of X and Y axis slides

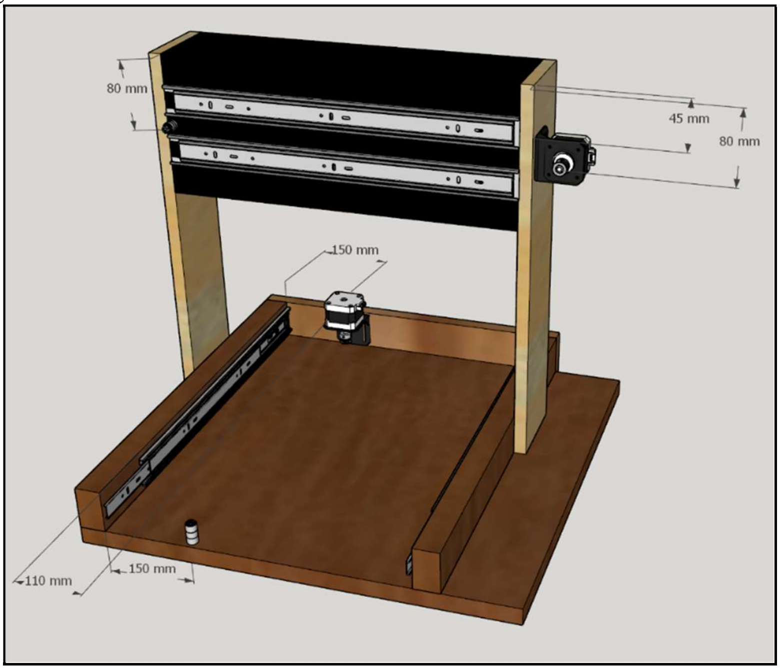


Source: prepared by the author (2024).

The telescopic slides used are of the 40 centimeter model to support up to 50 kilos, usually used in carpentry for the construction of mobile parts such as drawers. These components are easily found in hardware stores for furniture construction and there are two most common types of slides, normal and reinforced. In this context, the reinforced model was chosen, due to the fact that it has more bearings in its structure. A very important detail was the observation of the fixing of the slides at the perfect angle of 90 degrees, because they must easily travel their course, as can be seen in Figure 15 and were fixed with 3.5 x 15 mm screws. The last stage, that is, the thinnest part of the slide, had a sawed piece and was motivated by aesthetic objectives, so as not to show out of the printer, when it is at the end of the X-axis stroke.

The Y-axis motor, by virtue of taking advantage of the structure of the CNC prototype and using less space, was installed inverted. It was fixed on a 90-degree steel bracket, with standard drilling of Nema 17 motors. The installed pulleys are compatible with 20 teeth GT2 belt and 6 mm thickness. The pulleys of the Y and X axes were installed by means of a superb screw of 3.5 x 35 mm, with three spacers to be at the height of the motor pulley. The spacers used were 3 6 mm nuts combined with washers. The X-axis motor was installed in its normal position, with steel support with 90 degree angle. The drilling of the bracket also follows the drilling pattern of Nema 17 motors, as illustrated in Figure 16.

Figure 16 - Installation of the motor and sheaves GT X and Y axes

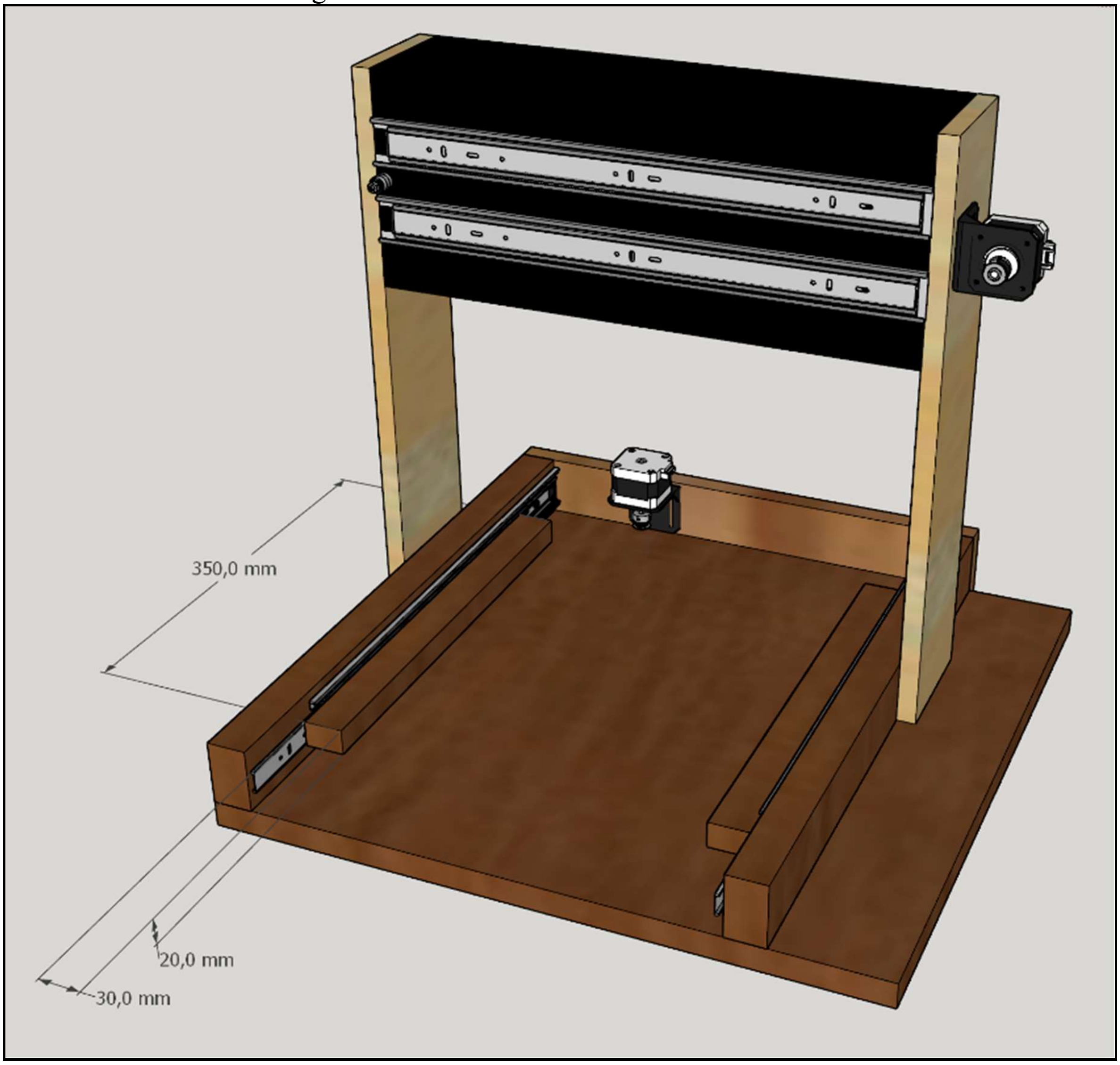


Source: prepared by the author (2024).

In the initial photos of the prototype, the project would be made with threaded bars on the X and Y axes, but due to speed and maintenance, it was opted for an improvement with the

GT2 pulleys that yielded a higher speed, in addition to facilitating the movement of the axes when the printer is off, as seen in **Erro! Autoreferência de indicador não válida.**. It can also be noted that this system will allow maintenance and installation in a more simplified way. It is observed that the GT2 belt with the time of use and natural wear of the rubber, gaps appear, making it necessary constant retightening, approximately every 20 hours of printing.

Figure 17 - Side columns of the Y-axis slides



Source: prepared by the author (2024).

Side columns of the Y-axis slides are optional in the design. In the case of this prototype, they were used, due to reusing the material that was already in the prototype of the CNC router, but the base for the heated table can be installed directly on the slides without the need for these columns. The columns in question are made of cinnamon wood and were fixed with 3.5 x 10 mm screws on the inside of the Y-axis slide, as shown in In the initial photos of the prototype, the project would be made with threaded bars on the X and Y axes, but due to speed and maintenance, it was opted for an improvement with the GT2 pulleys that yielded a higher speed, in addition to facilitating the movement of the axes when the printer is off, as seen in **Erro! Autoreferência de indicador não válida.**. It can also be noted that this system will allow maintenance and installation in a more simplified way. It is observed that the GT2 belt with the time of use and natural wear of the rubber, gaps appear, making it necessary constant retightening, approximately every 20 hours of printing.

.

Figure 18 - Base and attachment of the Y-axis heated table

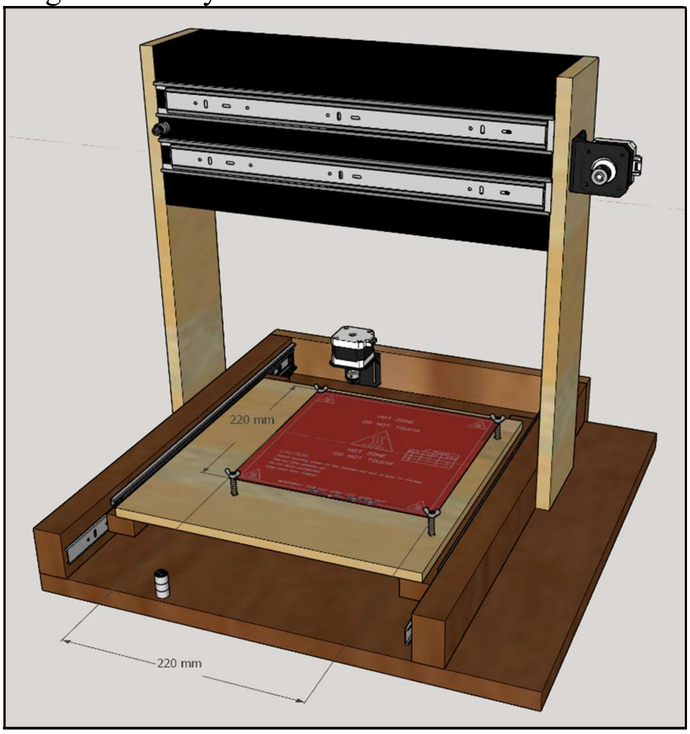
Source: prepared by the author (2024).

The base of the heated table consists of a 320 x 320 mm wood, in 10 mm MDF, reused from the prototype of the CNC router and were fixed to the side columns of the Y axis. Also in this base, 4 holes were made with a 3 mm drill and 4 standar M3 screws were placed from bottom to top, with springs and wing nuts, to later receive the heated table, as shown in Side columns of the Y-axis slides are optional in the design. In the case of this prototype, they were used, due to reusing the material that was already in the prototype of the CNC router, but the base for the heated table can be installed directly on the slides without the need for these columns. The columns in question are made of cinnamon wood and were fixed with 3.5 x 10 mm screws on the inside of the Y-axis slide, as shown in In the initial photos of the prototype, the project would be made with threaded bars on the X and Y axes, but due to speed and maintenance, it was opted for an improvement with the GT2 pulleys that yielded a higher speed, in addition to facilitating the movement of the axes when the printer is off, as seen in **Erro! Autoreferência de indicador não válida.**. It can also be noted that this system will allow maintenance and installation in a more simplified way. It is observed that the GT2 belt with the time of use and natural wear of the rubber, gaps appear, making it necessary constant retightening, approximately every 20 hours of printing.

.

Figure 18. The drilling of the screws occurred through the holes of the heated table, which was used as a drilling template. The standard M3 screws, springs, washers and wing nuts were purchased from the Coremma company located in the city of Blumenau, Santa Catarina.

Figure 19 - Physical installation of the heated table



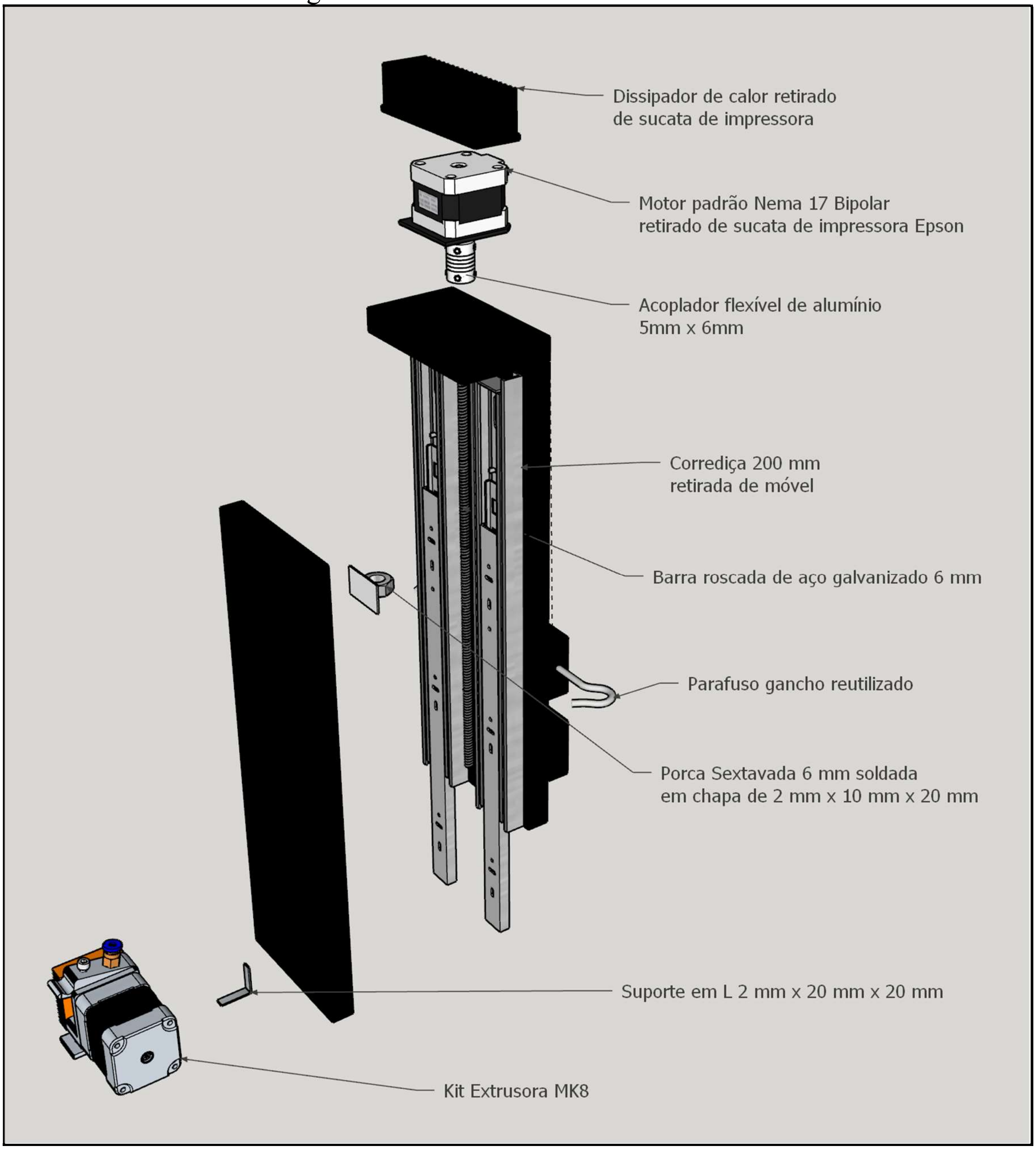
Source: prepared by the author (2024).

At this stage, the heated table was only placed in its place, but later it was removed for the installation of the temperature sensor and power cables, as illustrated in Figure 19. This heated table, when it will go into operation, will be overlaid by a 2 mm thick glass measuring 200 x 200 mm, purchased at Vidraçaria NM located in the city of Blumenau, Santa Catarina.

3.3.1.3 Montagem do eixo Z

The Z axis concentrates the most complex mobile structure and due to this fact, several detailed drawings were made and as shown in Figure 20, all the parts used in detail follow. An important issue to mention during assembly is the alignment of the Z-axis motor with the coupler and threaded bar, which must be at an exact angle of 90 degrees, since if there is variation, the system at some point in the stroke will lock or become heavy, impairing performance or even locking. The heat sink installed on top of the motor occurred due to heating that was later solved in part with the reduction of voltage in the stepper motor controller. The system that offers traction to the moving part of the shaft was taken from the CNC design, which consists of a 2 mm x 10 mm x 20 mm steel plate, with a 6 mm hexagonal nut welded at a 90-degree angle.

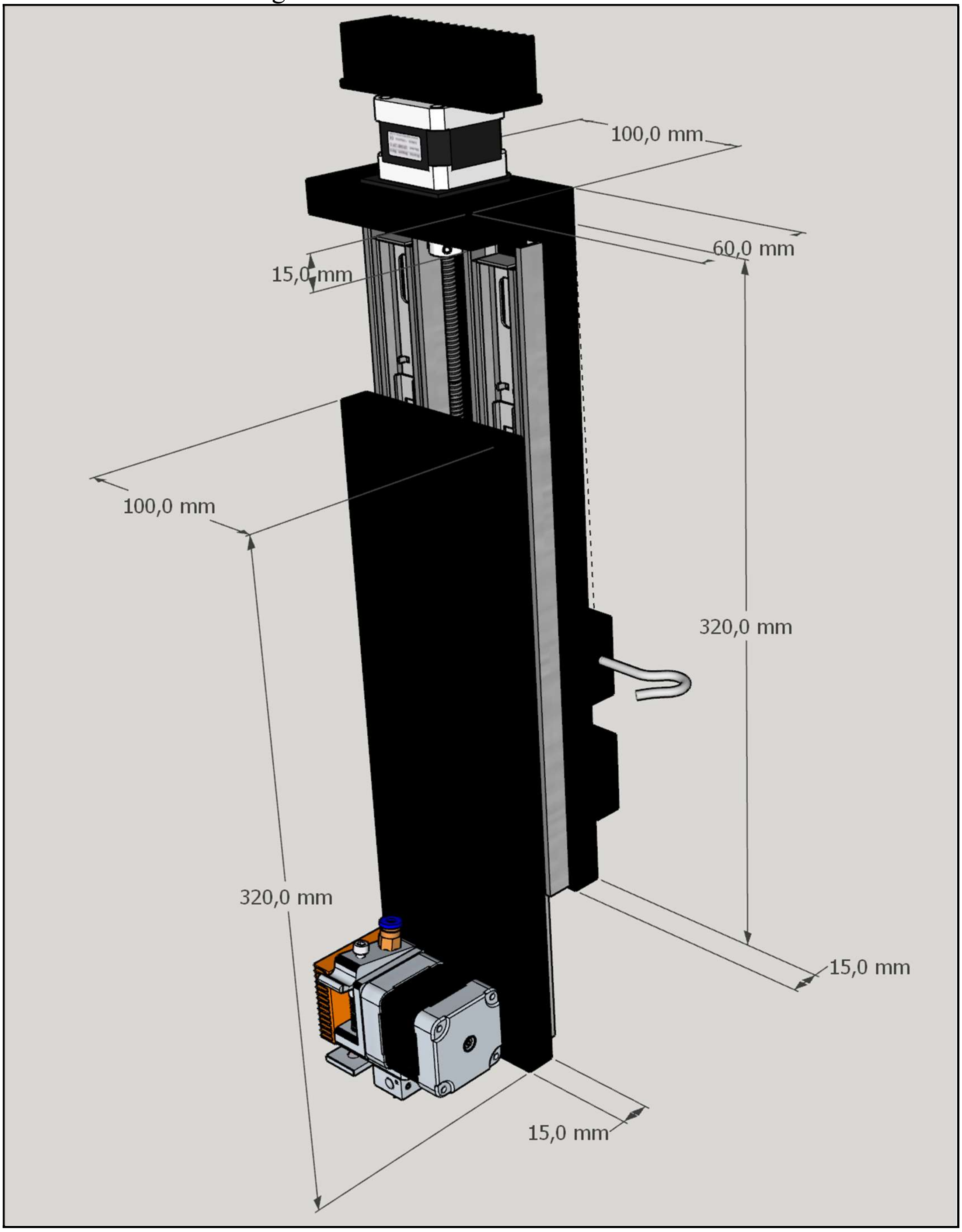
Figure 20 – Z-Axis – Detailed Side View



Source: prepared by the author (2024).

A difference in relation to related works is that this conception of the Z axis was designed to operate only with one motor, aiming at simplicity and reduction of costs and weight. Usually the Z axis has two motors, one being arranged at each end of each tower and must work in synchrony, due to the weight of the set. Usually, synchronization problems occur between the two motors, due to factors such as alignment of the motors' threads, gaps in the nuts or belts, and timing of the threaded bars.

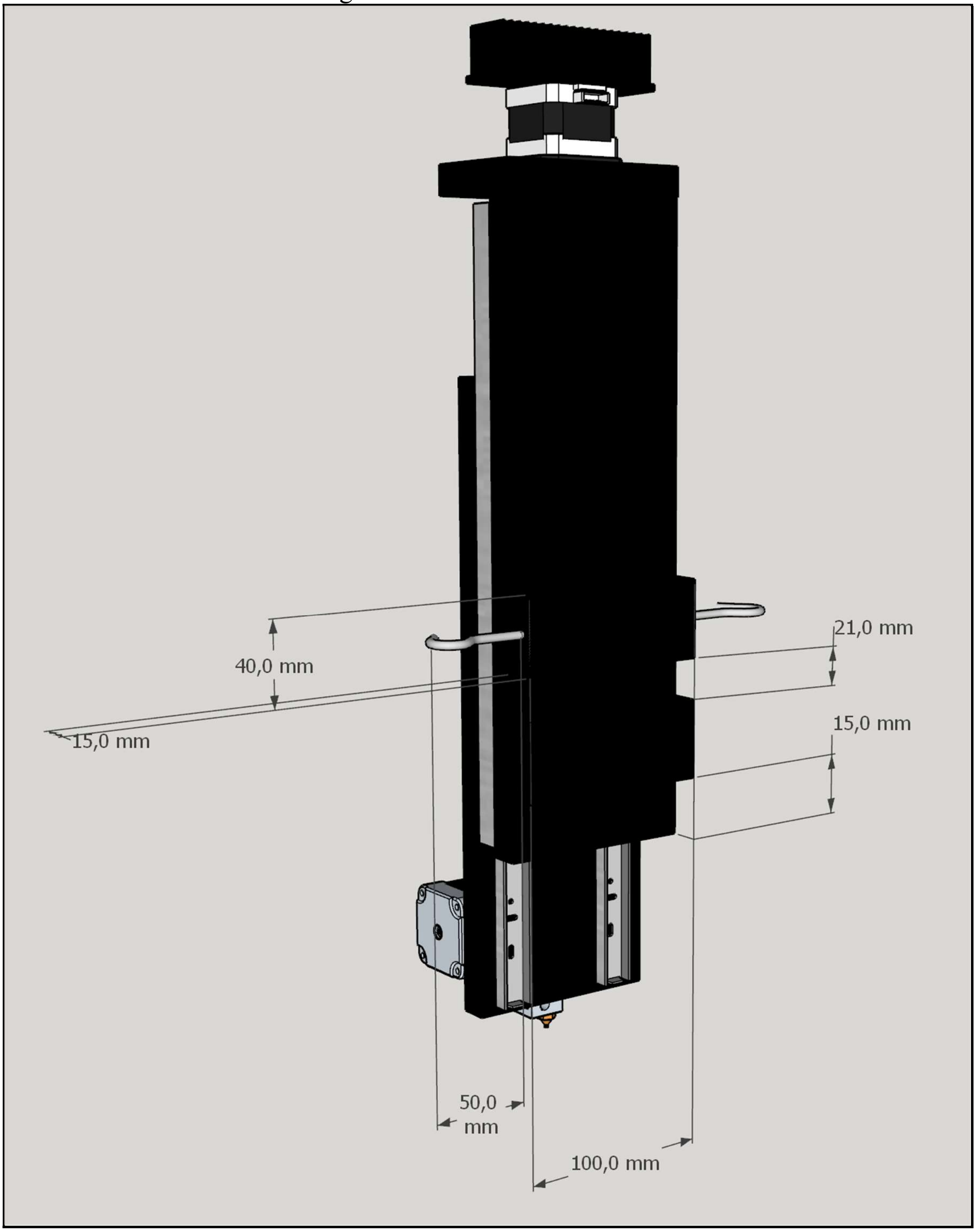
Figure 21 - Z-Axis – Mounted Side View



Source: prepared by the author (2024).

The Z-axis structure consists of two 200 mm telescopic slides, taken from an old piece of furniture, and the other MDF sheets were reused from the author's personal collection and cut by the company Compensados Keunecke, located in the city of Blumenau, Santa Catarina, in the measurements described in Figure 21. The fixing was carried out with superb screws of 3.5 x 25 mm and the hooks that move the axis to the left and right on the X axis, are hooks reused from an old clothesline of the author's residence.

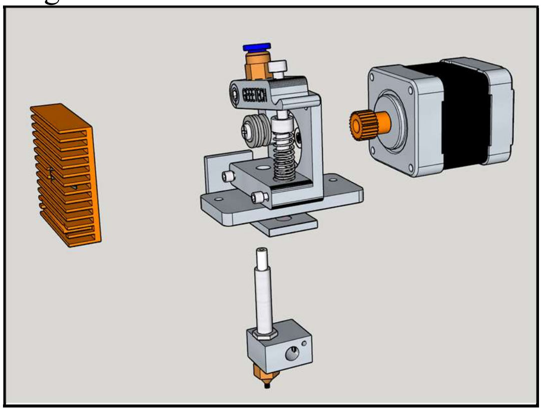
Figure 22 - Z Axis – Rear View



Source: prepared by the author (2024).

At the rear of the Z axle, as shown in Figure 22, you can see the view of the axle travel operation and the main span that the 6 mm GT2 belt will pass. This space is designed to leave a minimum of 5 millimeters on all sides for the GT2 belt to operate without the possibility of scraping or tangling in any part of the moving structure.

Figure 23 – Z-Axis – Detailed Extruder

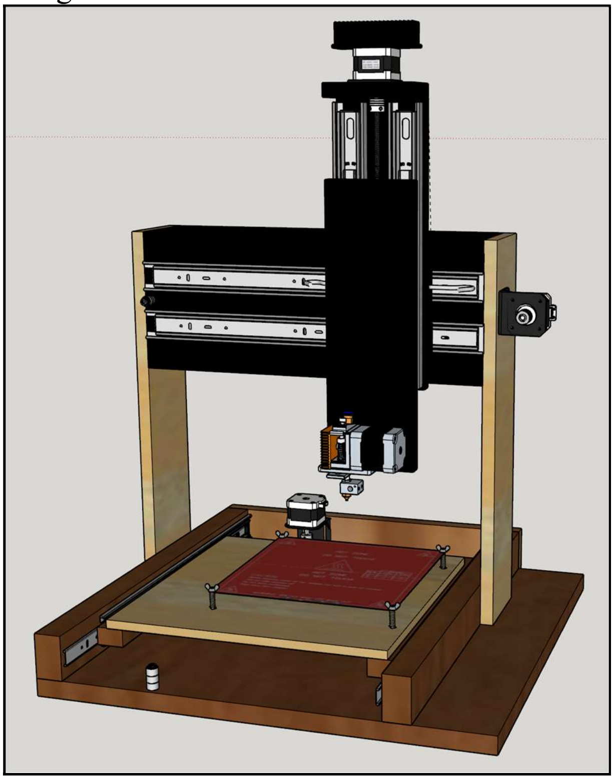


Source: prepared by the author (2024).

The MK8 extruder was purchased manufactured and its structure is represented in Figure 23 At the rear of the Z axle, as shown in Figure 22, you can see the view of the axle travel operation and the main span that the 6 mm GT2 belt will pass. This space is designed to leave a minimum of 5 millimeters on all sides for the GT2 belt to operate without the possibility of scraping or tangling in any part of the moving structure.

for didactic purposes only. The filament is pulled by the central part of the extruder, which is pulled by the motor and is conducted to the bottom, called HotEnd, which when heated, melts the filament, at the coordinates managed by the firmware that operates the microcontroller. The HotEnd used in this study is 0.4 mm and depending on the speed at which the extruder motor acts, the filament comes out thinner or thicker, and can generate a filament from 0.1 mm to 0.4 mm. The heat sink has the function of cooling the filament, so that it melts only in the HotEnd and does not obstruct the passage of filament with premature melting.

Figure 24 - Z-Axis Mounted on the X-Axis



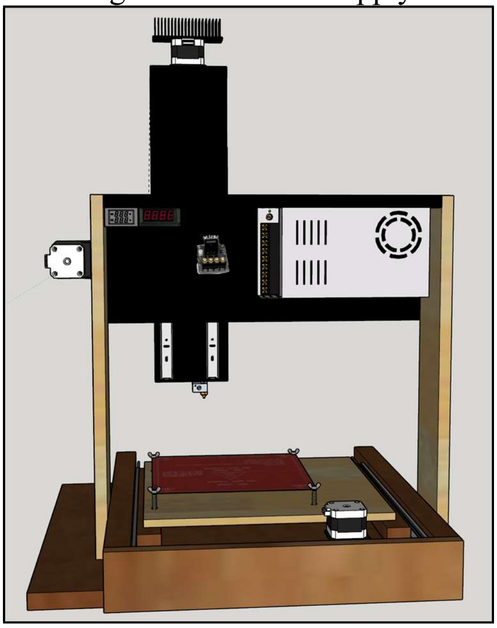
Source: prepared by the author (2024).

After completing the assembly of the Z-axis, the structure was coupled to the X-axis slides of the main structure, as shown in Figure 24.

3.3.1.4 Electronic components assembly

At this stage, all electronic components were installed, including the power supply, Arduino boards (Arduino, 2024) and Ramps (RepRap Contributors, 2024), limit switches, stepper motor controllers and LCD display, as shown in Figure 25.

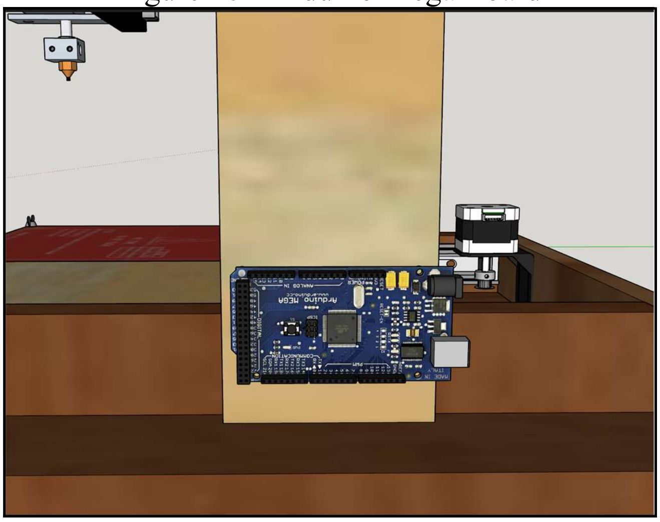
Figure 25 - Power Supply



Source: prepared by the author (2024).

Figure 25, as illustrated, you can see the positioning of the 12V 30-amp power supply, the heated table power module, and the current, amperage, and temperature meters. They were fixed with 2.5 x 10 mm screws.

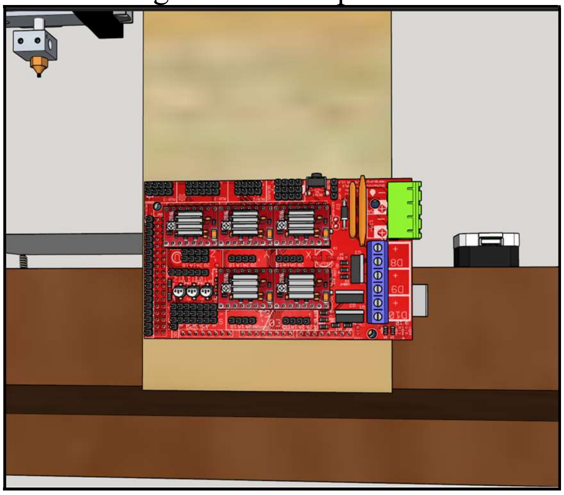
Figure 26 - Arduino Mega Board



Source: prepared by the author (2024).

The Arduino Mega 2560 board (Arduino, 2024) was fixed to the base of the right side column, initially fixed with screws isolated from the board, directly on the wood as illustrated in Figure 26..

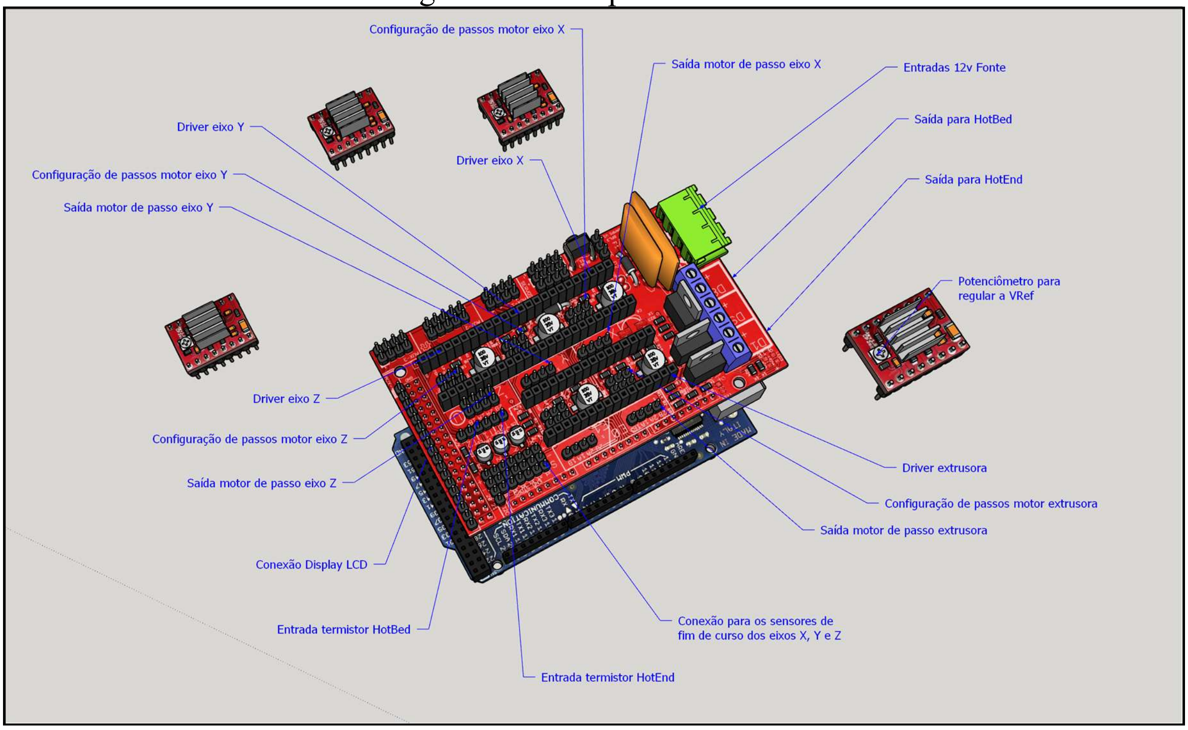
Figure 27 - Ramps Plate



Source: prepared by the author (2024).

The Ramps board (RepRap Contributors, 2024) version 1.4 was attached to the Arduino Mega 2560 board (Arduino, 2024), being superimposed, as illustrated in Figure 27.

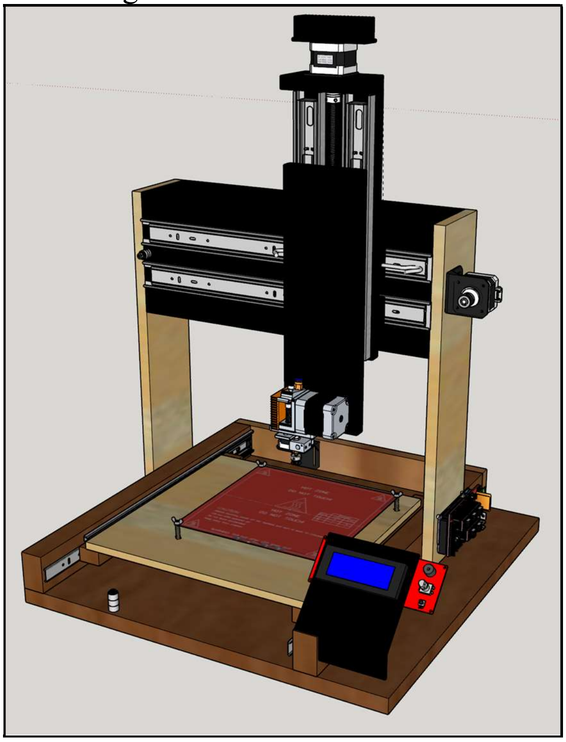
Figure 28 – Ramps Plate Detail



Source: prepared by the author (2024).

The description of the main connections used in the project is illustrated in Figure 28, in which the Ramps board (RepRap Contributors, 2024) version 1.4 is coupled to the Arduino Mega 2560 board and the stepper motor controllers are coupled to the Ramps board (RepRap Contributors, 2024).

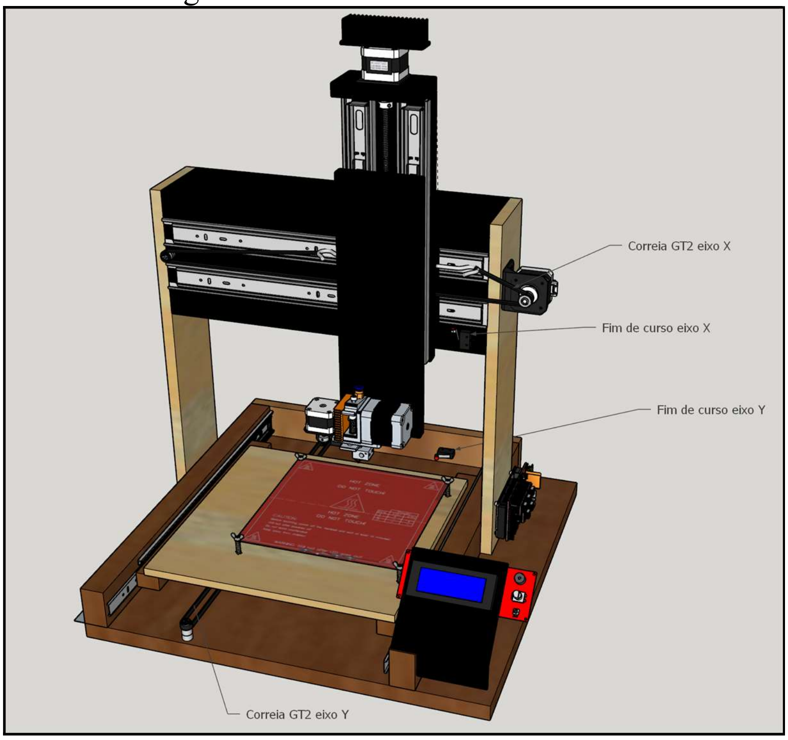
Figure 29 – LCD Viewfinder



Source: prepared by the author (2024).

The assembly of the LCD display structure did not require complexity and was fixed to the wood with screws, as shown in Figure 29. The LCD display board was attached to the display cover with old computer cabinet screws, due to the reduced thickness and thread pattern being specific to electronic components.

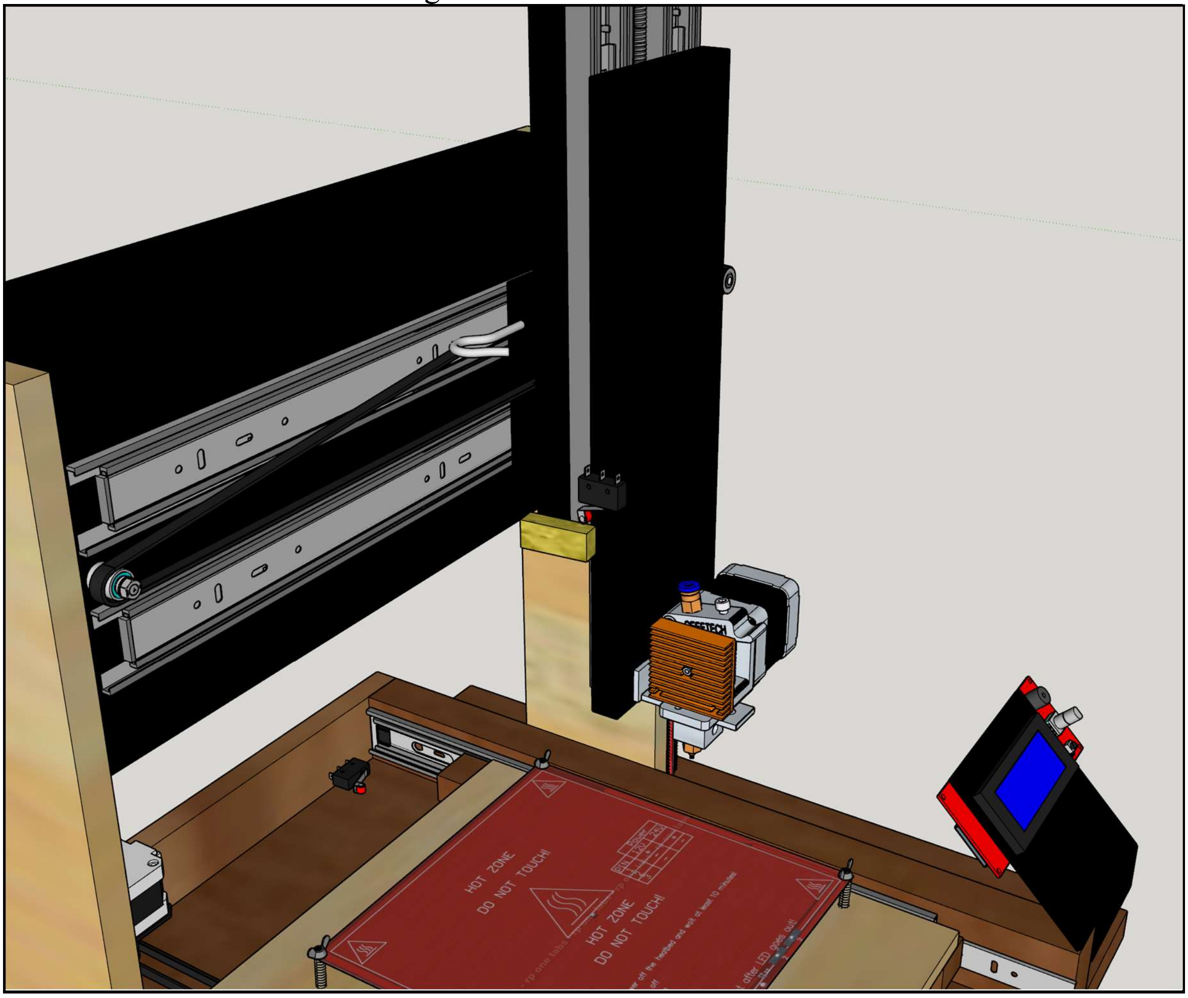
Figure 30 - Limit switch and GT belt



Source: prepared by the author (2024).

The limit switches of the X and Y axes were each coupled on its axis, as illustrated in Figure 30. They were fixed in the fixed parts of the structure and are intended to be activated when the end of the limit of an axis occurs. They were fixed with screws and to achieve the height, plastic spacers of 10 mm each were installed. The GT belts were tensioned and fixed with a nylon plastic strap.

Figure 31 - Z-axis limit switch

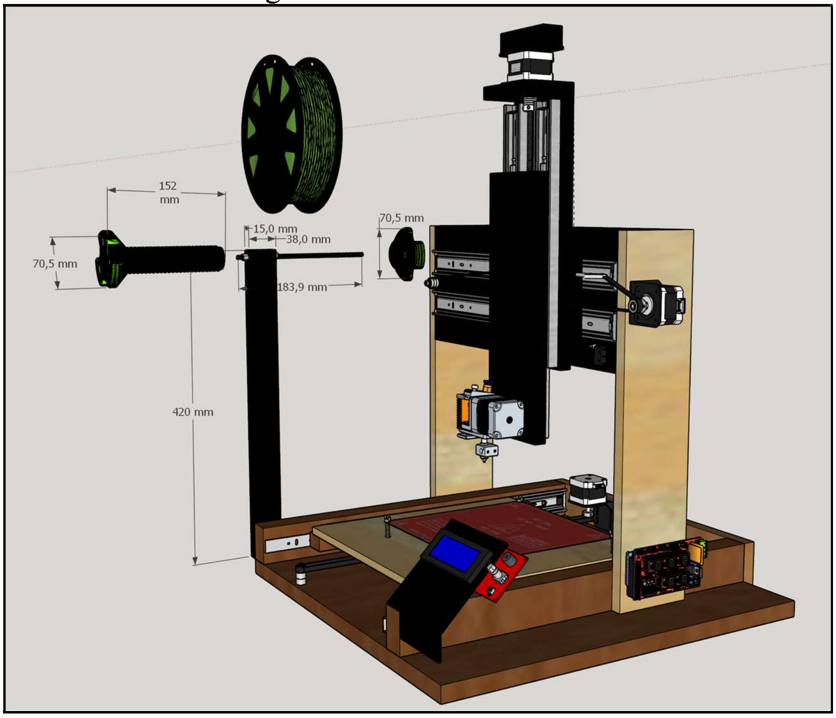


Source: prepared by the author (2024).

The Z-axis limit switch sensor is the most complex in the system, because it performs in addition to stopping the Z-axis, it must be adjusted to stop the axis approximately 0.75 mm from the glass that overlaps the heated table, as shown in Figure 31. It differs from the others in that it has been fixed in a movable part, while the others are positioned in a fixed part. The standard 0.75 mm of space in relation to the extruder nozzle and the glass are necessary for the correct adhesion of the melted filament at the time of printing a part in 3D, together with the leveling of the four corners of the heated table, which occurs through the adjustment through the butterfly screws.

3.3.1.5 Mounting the filament feeder

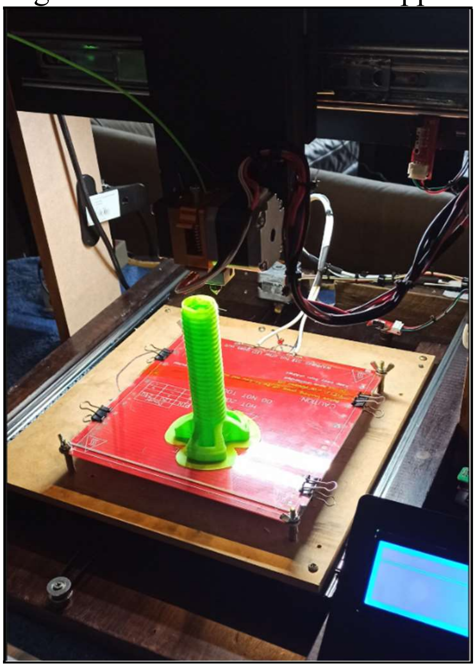
Figure 32 - Filament Feeder



Source: prepared by the author (2024).

The filament feeder was coupled to the wooden base so that the filament is made available to the printer, without the formation of knots or roll jams, as shown in Figure 32. It was built using pieces of MDF cuts and with remnants of the threaded bars used in the construction of the Z-axis.

Figure 33 - Filament Roller Support



Source: prepared by the author (2024).

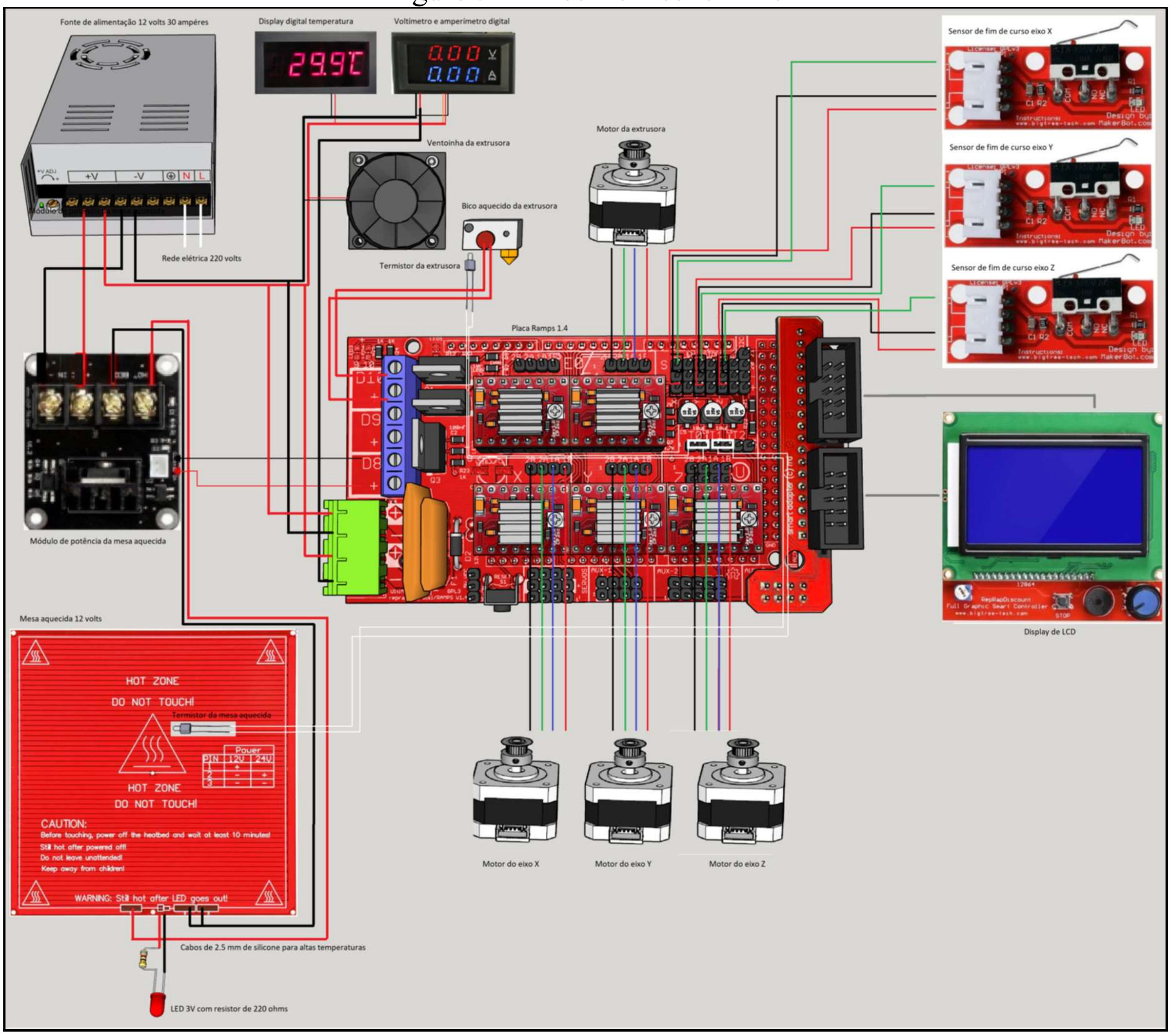
The filament roll holder was printed by the printer itself with the PLA (Polylactic Acid, 2024) filament type in the thickness of 1.75 millimeters. The choice of PLA material was due to the fact that this type of filament is compatible with the temperature of the table and extruder that the prototype is capable of printing. This part ensures that the roller can operate without jamming and has an inverted thread that allows easy maintenance, as shown in Figure 33.

Finally, the physical and mechanical structure of the printer is finalized and the next step is the initial configuration of the firmware and connection of the electronic components in order to make the prototype operational.

3.3.2 Techniques and tools used

The electrical diagram of the printer connection is shown in Figure 34, in which it is possible to highlight all the connection of the electronic components of the sensors, actuators and power source.

Figure 34 - Electrical schematic



Source: prepared by the author (2024).

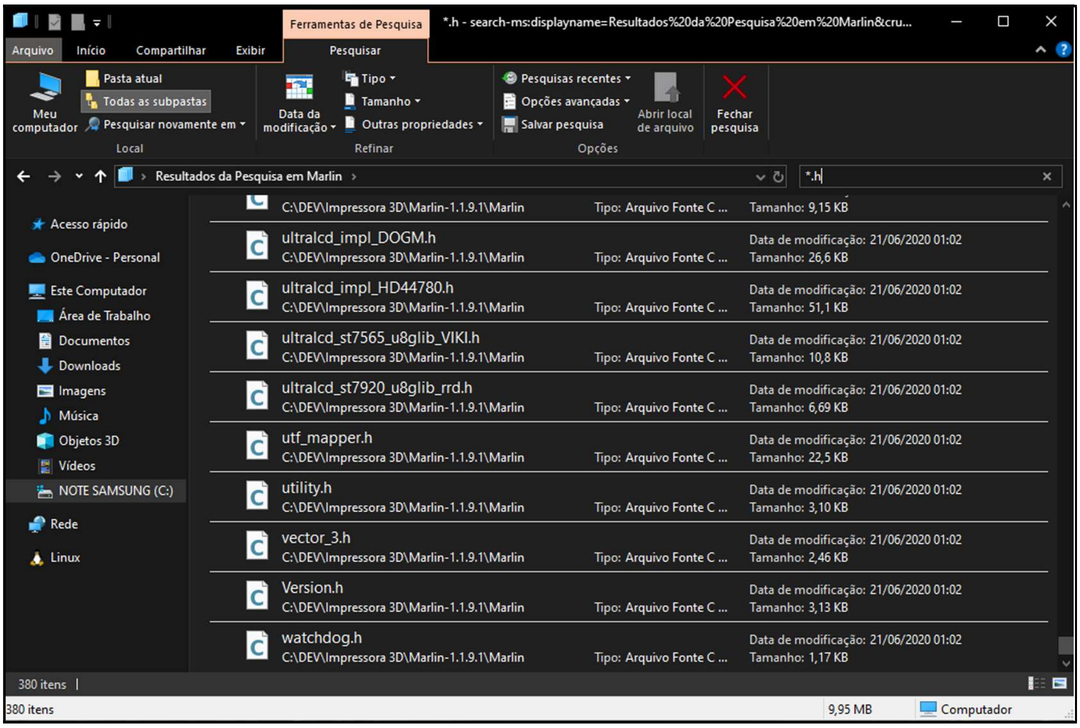
The components were connected according to the connection scheme and the power cables had their ends soldered with tin and then the coupling of connection terminals was carried out, to facilitate installation and maintenance. During this stage, the author suggests not fixing the cables with plastic clips, because during the tests, several adjustments and repositioning of the cables will be necessary.

3.3.3 Firmware Installation and Configuration

The system was assembled in parts incrementally, with the first part consisting of the configuration of the Marlin firmware (Zalm, 2011) with the Arduino Mega 2560 (Arduino, 2024), Ramps (RepRap Contributors, 2024) version 1.4 and LCD display boards. The Arduino Mega 2560 board was plugged directly into the computer's USB port for configuration.

The *Marlin firmware* (Marlin, 2020) version 1.1.9.1 and the Arduino IDE application (Arduino, 2021), version 1.8.19, were downloaded. The file with the source code of the firmware used in this study was unzipped in the folder `C:\DEV\3D Printer\Marlin-1.1.9\Marlin`. The *Marlin* Firmware has several files in its source code, totaling 380 files, as illustrated in Figure 35.

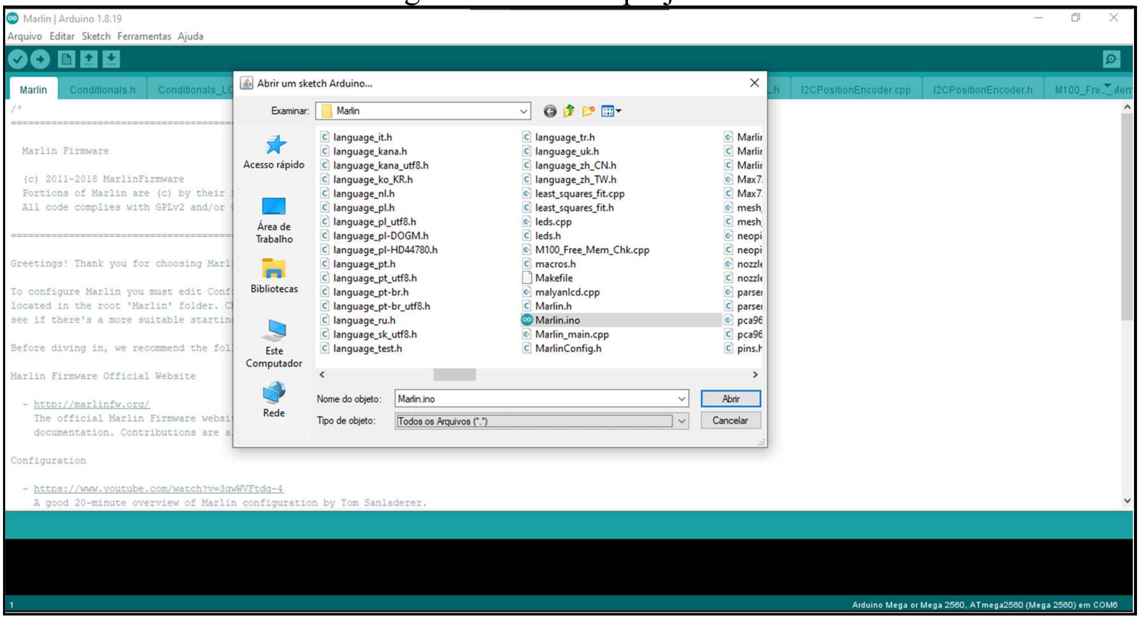
Figure 35 - Marlin Firmware Files



Source: prepared by the author (2024).

The installation of the integrated development environment (IDE) of Arduino version 1.8.19 (Arduino, 2021) took place in a simple way without the need for specific configurations. The author opted for a version prior to the current one, because version 2.3.2 was very slow on the computer where the study was conducted. After the installation of the development environment was complete, the main file of the *Marlin* Firmware project, named `Marlin.ino`, was opened, as illustrated in Figure 36.

Figure 36 - Marlin project file



Source: prepared by the author (2024).

The source code of all *Marlin* firmware is written in the C language and the scope of the changes in this study were made to the `configuration.h`, `_bootscreen.h` and `configuration_adv.h` files. The main operating parameters are in the `configuration.h` file and have been modified as shown in Chart 3. Changes are composed of changing the values of variables and constants in the source code.

Chart 3 - Configuration of the Marlin Firmware parameters - configuration.h

Parameter	Value	Description
#define STRING_CONFIG_H_AUTHOR	"(Jonas Fernando Schuh, 2024)"	Firmware Configuration Author
#define SHOW_CUSTOM_BOOTSCREEN	uncomment	Enables to show bitmap on boot screen
#define BAUDRATE	115200	This parameter determines the speed at which the computer communicates with the printer
#define CUSTOM_MACHINE_NAME	"Jonas F Schuh v1.5"	Optional parameter to customize the LCD display. Used for adjustment version

#define MOTHERBOARD	BOARD_RAMPS_14_EFB	Defines the type of electronic board used, in this case the RAMPS 1.4 model with power outlets for hotend, exhaust fan and heated bed respectively
#define DEFAULT_NOMINAL_FILAMENT_DIA	1.75	Filament Diameter Configuration for Volumetric Calculations
#define TEMP_SENSOR_0	1 // 1: 100k thermistor - best choice for EPCOS 100k (4.7k pullup)	Defines which type of thermistor will be used in the E0 extruder
#define TEMP_SENSOR_BED	75 // 75: 100k Generic Silicon Heat Pad with NTC 100K MGB18-104F39050L32 thermistor	Defines which type of thermistor will be used in the hotbed
//Ultimaker #define DEFAULT_Kp	25.32	Sets the value of the Gain Proportional Controller to Hotend. Note: Value generated by auto tune
//Ultimaker #define DEFAULT_Ki	2.13	Sets the value of the integral controller to Hotend. Note: Value generated by auto tune
//Ultimaker #define DEFAULT_Kd	75.18	Sets the value of the derivative controller to Hotend. Note: Value generated by auto tune
#define PIDTEMPBED	uncomment	Enable or PID for Hotbed
#define MAX_BED_POWER	250	Limits the duty cycle of the heated bed. 255 indicates total current.
#define DEFAULT_bedKp	372.09	Sets the value of the Gain Proportional Controller for Hotbed. Note: Value generated by auto tune
#define DEFAULT_bedKi	53.43	Sets the value of the integral controller to Hotbed. Note: Value generated by auto tune
#define DEFAULT_bedKd	547.75	Sets the value of the derivative controller to Hotbed. Note: Value generated by auto tune
#define ENDSTOPPULLUPS	comment	Disables pullup for all limit switches to avoid a floating state
#define X_MIN_ENDSTOP_INVERTING	TRUE	Enables to reverse the logic of the limit switch to the minimum position at X

#define Y_MIN_ENDSTOP_INVERTING	TRUE	Enables to reverse the limitEnables to reverse the logic of the limit switch to the minimum position at Z switch logic to the minimum position in Y
#define Z_MIN_ENDSTOP_INVERTING	TRUE	Enables to reverse the logic of the limit switch to the minimum position at Z
#define DEFAULT_AXIS_STEPS_PER_UNIT	{80, 80, 5100, 185.20}	Number of steps required in mm for respectively, X, Y, Z, E0
#define DEFAULT_MAX_FEEDRATE	{300, 300, 5, 25}	Sets the maximum speed in mm/s to respectively X, Y, Z, E0
#define DEFAULT_MAX_ACCELERATION	{1000, 1000, 5, 10000}	Sets the maximum acceleration in mm/s to respectively X, Y, Z, E0
#define DEFAULT_TRAVEL_ACCELERATION	300	Sets the acceleration speed of the axes for travel
#define Z_MIN_PROBE_USES_Z_MIN_ENDSTOP_PIN	comentado	This option disables probe option connected to the Z Min limit switch pin
#define PROBE_MANUALLY	descomentado	This option enables manual table leveling
#define INVERT_X_DIR	TRUE	Reverses the direction of rotation of the stepper motor on the X-axis
#define INVERT_Y_DIR	FALSE	Reverses the direction of rotation of the stepper motor on the Y-axis
#define INVERT_Z_DIR	TRUE	Reverses the direction of rotation of the stepper motor on the Z-axis
#define X_BED_SIZE	175	Sets the print bed size on the X axis
#define Y_BED_SIZE	175	Sets the print bed size on the Y-axis
#define MESH_BED_LEVELING	Uncommented	Enables manual grading of the print bed in grid format
#define GRID_MAX_POINTS_X	2	Sets the number of points that will be tested on table leveling for the X-axis
#define LCD_BED_LEVELING	Uncommented	Enables table leveling via LCD display via menu

#define EEPROM_SETTINGS	Uncommented	Enables changing firmware parameters directly on Default Table Temperature Value for PLAthe LCD display and recording to the EEPROM of the microcontroller
#define PREHEAT_1_TEMP_BED	60	Default table temperature value for PLA
#define PREHEAT_1_FAN_SPEED	0	Standard fan speed for PLA. In this case it is zero because the fan was connected directly to the power supply to always stay on.
#define PREHEAT_2_TEMP_HOTEND	210	Hotend Default Temperature Value for ABS
#define PREHEAT_2_TEMP_BED	78	Hotbed default temperature value for ABS. Original would be 110, but this desktop configuration fails to reach that figure.
#define PREHEAT_2_FAN_SPEED	0	Standard fan speed for ABS. In this case it is zero because the fan was connected directly to the power supply to always stay on.
#define PRINTCOUNTER	Uncommented	Optional parameter, displays statistics of how many prints have been made on the printer.
#define LCD_LANGUAGE	pt-br	Sets the language to be displayed on the LCD display
#define SDSUPPORT	Uncommented	Enables support for direct SD card reading on the LCD display
#define REPRAP_DISCOUNT_FULL_GRAPHIC_SMART_CONTROLLER	Uncommented	Select the LCD display graphics controller

Source: prepared by the author (2024).

The source code file of the `configuration_adv.h` file contains the advanced and more firmware-specific settings. During the development of the prototype, several configurations were made, but the final version after testing and adjustments resulted in only one change that is shown in Chart 4.

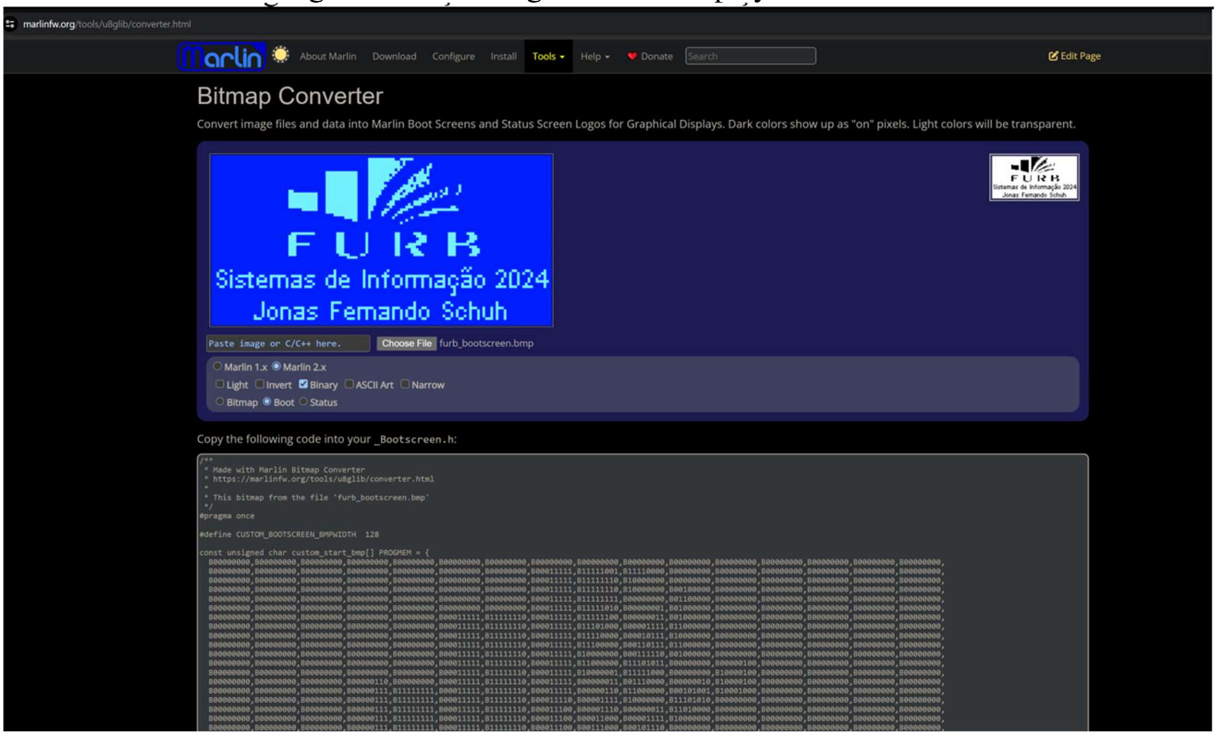
Chart 4 – Marlin Firmware Parameter Configuration – configuration_adv.h

Parameter	Value	Description
#define THERMAL_PROTECTION_BED_HYSTERESIS	4	Parameter of thermal protection by software. If there is a variation of 4 degrees Celsius, the software stops automatically

Source: prepared by the author (2024).

Among the firmware features is the customization of the boot screen on the LCD display and happens by including the file `_Bootscreen.h` in the main folder of the Marlin firmware, *in the case of this study, it was included in the folder* `C:\DEV\3D Printer\Marlin-1.1.9\Marlin`.

Figure 37 - Creating the LCD Display Boot Screen



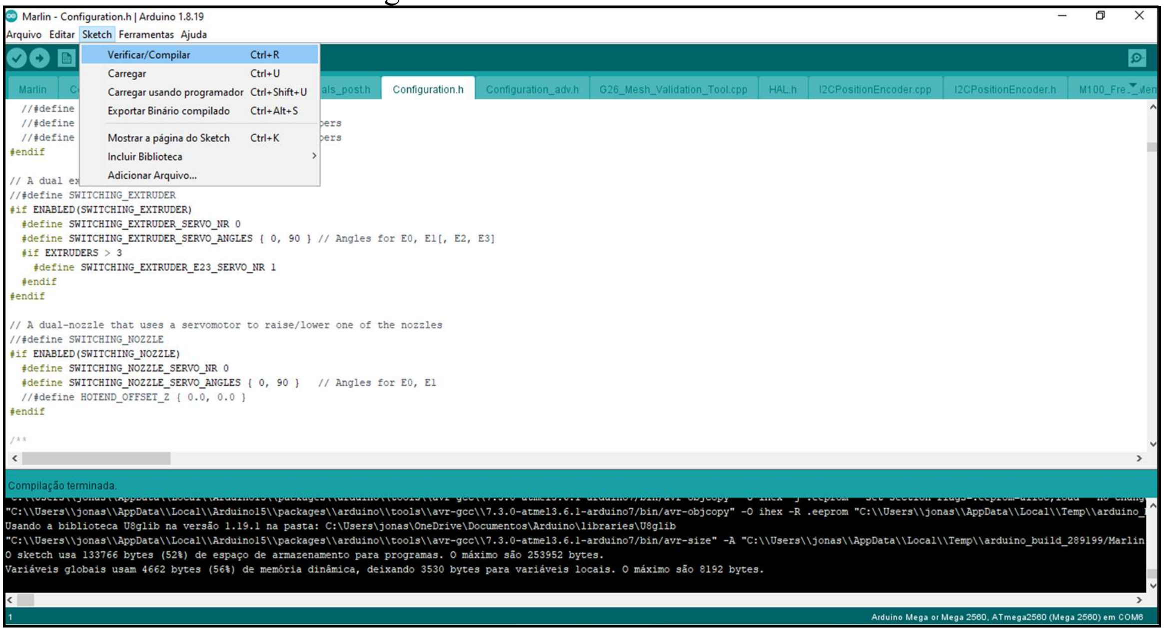
Source: prepared by the author (2024).

This file is automatically generated when accessing the *Marlin firmware page* (Zalm, 2011), Tools > `Bitmap Converter option`, as shown in Among the firmware features is the customization of the boot screen on the LCD display and happens by including the file `_Bootscreen.h` in the main folder of the Marlin firmware, *in the case of this study, it was included in the folder* `C:\DEV\3D Printer\Marlin-1.1.9\Marlin`.

, where a black and white bitmap file in the format of 128 x 64 pixels is selected and after loading the file, the page generates a file for download with the name `_Bootscreen.h`. This file must be included in the folder where the source code files for the *Marlin firmware are located*.

After all the files have changed, it becomes necessary to compile the firmware, through the `Sketch > Verify/Compile` option, as illustrated in Figure 38.

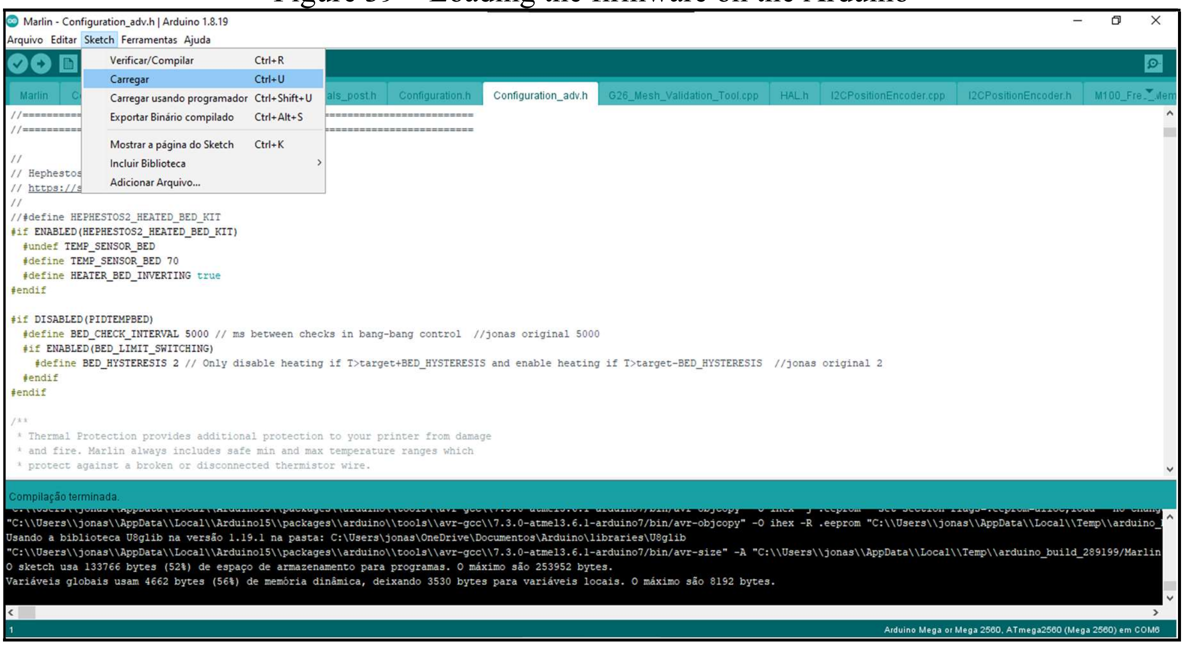
Figure 38 - Marlin Firmware Build



Source: prepared by the author (2024).

Finally, after all the firmware source code was compiled, the firmware was loaded into the microcontroller memory of the Arduino Mega 2560 board, through the `Sketch > Load` option, as illustrated in Figure 39.

Figure 39 – Loading the firmware on the Arduino



Source: prepared by the author (2024).

After loading the firmware into the microcontroller, it is automatically restarted and a boot screen is presented every time the microcontroller is restarted, where it is displayed for approximately 3 seconds, as seen in Figure 40.

Figure 40 - Boot Screen on the LCD Display

Source: prepared by the author (2024).

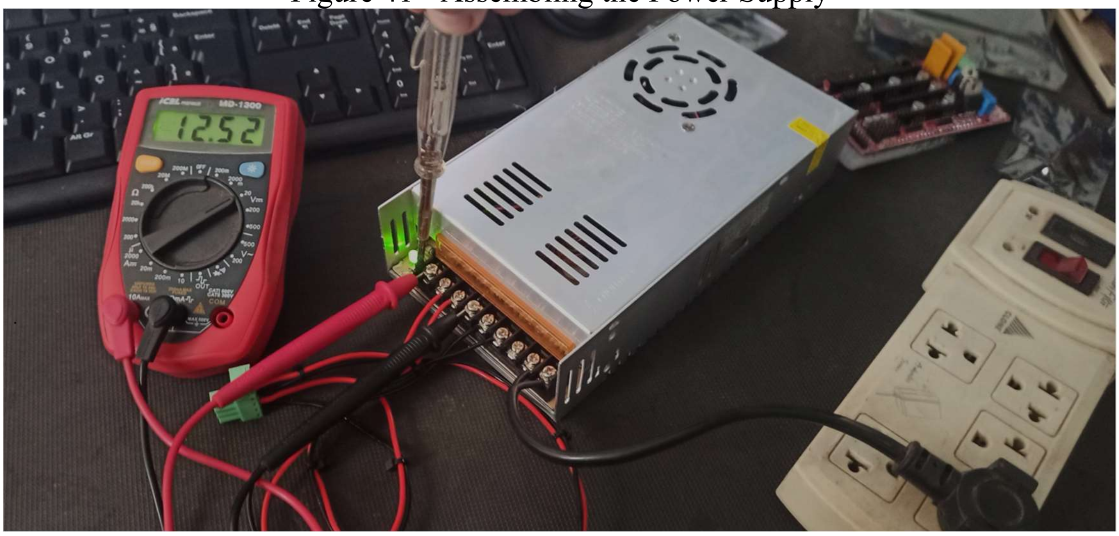
After the Arduino board and LCD display are functional, the next step is to configure the power supply of the entire system.

3.3.4 Stepper Motor Power Supply and Controller Configuration

The first step in configuring the power supply, as illustrated in Figure 41, is to check the voltage selection of the power supply, which is located on the side of the power supply structure and must be selected in the 220 volt position.

The 220 volt power cables for the network were used in the thickness of 1.5 mm, connected to the L and N terminals that respectively have Phase and Neutral. The grounding connection was not used, because in the place where the prototype was assembled, there is no grounding wiring, but the author recommends installation.

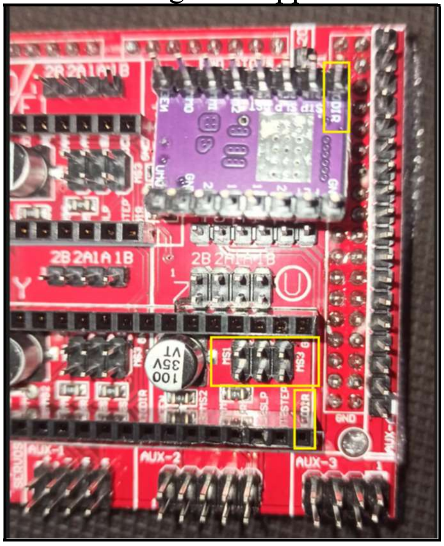
Figure 41 - Assembling the Power Supply



Source: prepared by the author (2024).

The 12-volt output cables that go to the Ramps board (RepRap Contributors, 2024), were used in the standard color red for the positive pole and black for the negative pole, in the thickness of 1.5 mm, as seen in Figure 41. The output voltage of the power supply was set to approximately 12.5 volts by regulating a small selector and was done by means of a small screwdriver.

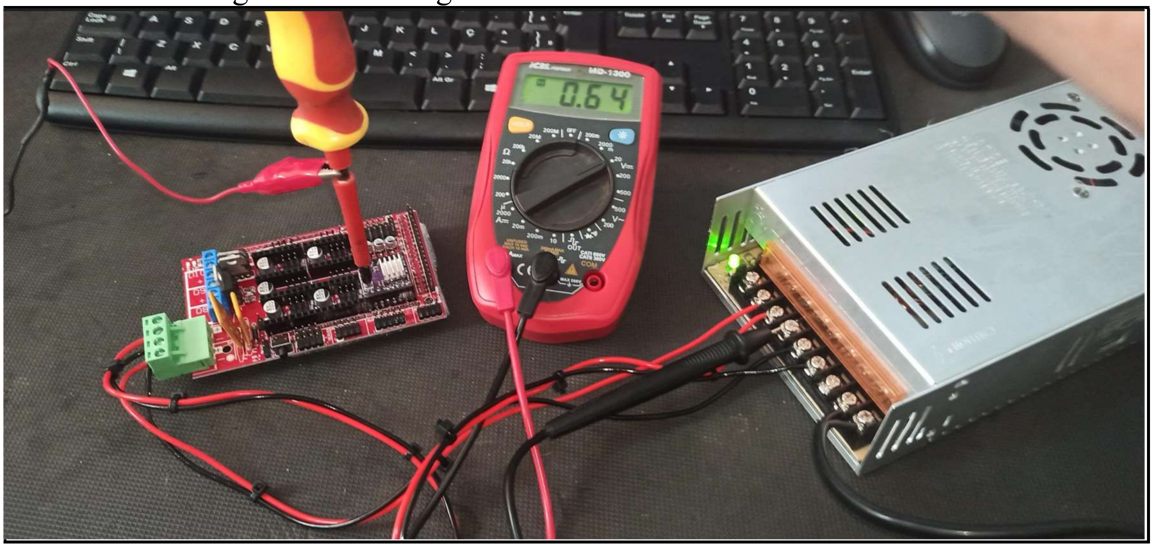
Figure 42 - Assembling the stepper motor controllers



Source: prepared by the author (2024).

The fitting of the stepper motor controllers requires attention to the correct placement of the position in relation to the Ramps plate. As illustrated in Figure 42, it can be seen that the "DIR" pin is written on the bottom of the controller and on the Ramps board there is also this inscription, where it must be fixed in this way.

Figure 43 – Setting the Reference Value on the Controller



Source: prepared by the author (2024).

After fitting the stepper motor controller, it became necessary to configure the reference voltage value (VREF) for each axis according to the specification of each stepper motor used. The reference value is a regulation that limits the current of energy that the controller will release to the stepper motor.

The configuration of the VREF occurs through a small adjustment that is located on the stepper motor controller of each axis and can be accessed with a Philips screwdriver, preferably with rubberized insulation, highlighted in The fitting of the stepper motor controllers requires attention to the correct placement of the position in relation to the Ramps plate. As illustrated in Figure 42, it can be seen that the "DIR" pin is written on the bottom of the controller and on the Ramps board there is also this inscription, where it must be fixed in this way.

Figure 43.

To measure the current voltage of the VREF, a multimeter set for direct current voltage must be used. The negative test lead of the multimeter should be plugged into the negative terminal of the source, and the positive test lead of the multimeter should be plugged straight into the potentiometer of the stepper motor controller. It is recommended to use alligator clips to connect the test tip to the Philips screwdriver for more practical and safer. The tip of the Philips screwdriver is made of metal, but it cannot touch any of the terminals of the stepper motor controller because it can cause a short circuit, resulting in damage to the component and other boards.

After this connection is made, the power supply is turned on and the measurement and adjustment of the voltage that is being supplied to the stepper motor controller is carried out.

The motors used in the prototype are recycled and taken from EPSON scrap printers. After searching the internet, it was not possible to find a specific electronic scheme for these motors, only a few generic information, such as operating voltage ranging from 6 to 42V and the most important information, how many amps the motor operates. The label of the Z-axis motor contains only Epson EM-257, without specification of specific model.

The X and Y axis motors contain only the Epson EM-267 inscription, but no electronic schematics have been found on the internet. The recommended standard for NEMA 17 motors (Motion King, 2024) was used, with an electrical diagram from the manufacturer MotionKing that has a current per phase of 1.7 A. The extruder motor is the NEMA 17 motor model HS4401, from the manufacturer MotionKing, which followed the same configuration pattern as the X and Y axes.

The stepper motor controller used in the project is the A4988 (Allegro, [2014?]), which in its technical specification, can control motors up to 35V and 2A per coil. Given this scenario, the initial configuration was chosen for half the maximum amperage that each motor supports, in order to extend the life of the motor and avoid heating, considering that the 3D printer will not need to use all the available torque of the motor.

The motor of the Z axis had its VREF set at 0.30 A and the motors of the X, Y and extruder axes, set at 0.45 A. In the first tests, the standard voltage that comes set on the driver was used, which is 0.75 A, but during the first tests, it was found that the motors heated up too much, and in the case of the Z axis, had the burning of several stepper motor controllers, until reaching this operating value of 0.30 A that became the stable configuration.

Another very important issue is the configuration of the steps that the controller will operate, represented on each axis by pins MS1 to MS3, highlighted in Figure 44.

Figure 44 - Resolution of Micro Step A4988 Driver

Resolução Micro-passo	MS3	MS2	MS1
Passo completo	0	0	0
meio passo	0	0	1
1/4 passo	0	1	0
1/8 passo	0	1	1
1/16 passo	1	1	1

Source: Murta (2022).

The most popular stepper motor controllers for Ramps boards (RepRap Contributors, 2024) are the A4988 and DRV8825 models. Each has specific micro-step resolution tables. Here in this section, only the configuration of the A4988 model will be aborted. This micro step setting increases the resolution of the printer, for example, if the step angle for a motor is 1.8 degrees with each step and total steps to cause a revolution is 200 steps, then if the driver is set to 1/16 step, it means that for the motor to move 1.8 degrees, it will have to take 16 steps.

Another point to note is the issue that the greater the number of steps, the lower the torque of the motor and in the case of this study, as the 3D printer requires precision and not force, this is the most appropriate configuration. The configuration occurred through combination jumpers, illustrated in Figure 42 and were all configured at the maximum resolution of the controller which is 1/16 step. As illustrated in Figure 44, the number 0 represents open and the number 1 represents closed, that is, with the jumper inserted, it represents 1. The MS1, MS2 and MS3 pins illustrated in Figure 44 received the addition of connection jumpers. This configuration was adopted for the X, Y, Z and extruder axis motors.

3.3.5 Heated table configuration

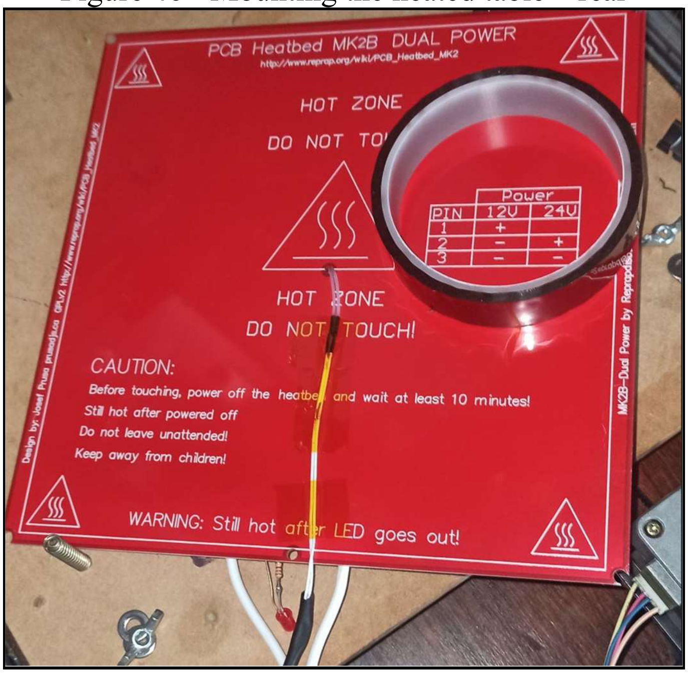
The heated table assembly is divided into two parts, the front and back. The front consists of the voltage configuration that the board will operate, as shown in Figure Figure 45, which should be compatible with the prototype's 12-volt source. The positive power cable was soldered to pin 1 of the table and the negative cable to pins 2 and 3. An LED was also soldered to the table, connected to a 220 ohm resistor to operate at 12 volts.

Figure 45 - Mounting the heated table – front

Source: prepared by the author (2024).

The power cables of the table must withstand high temperatures, since the table of this project can reach up to 80 degrees. The specification of the cable used is silicone for up to 220 degrees Celsius, at a thickness of 2.5 mm, as the table uses up to 11 A for heating. The jumper of pin 2 and 3 of the positive pole must also be 2.5 mm thick.

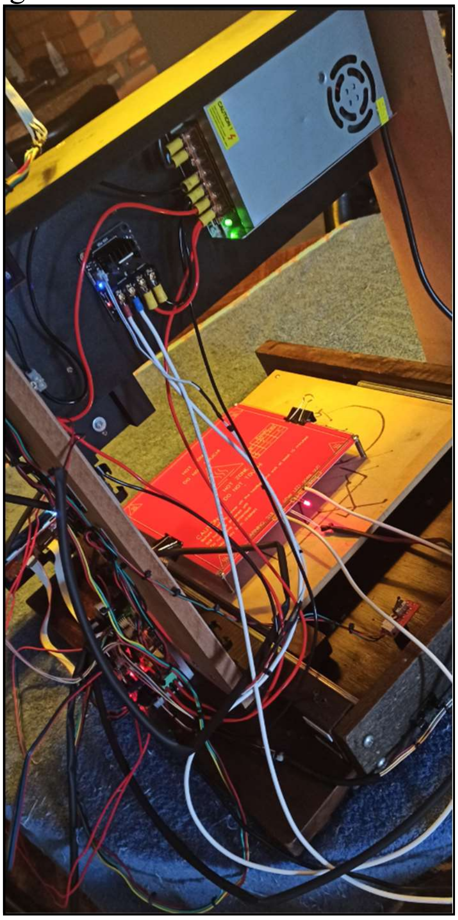
Figure 46 - Mounting the heated table – rear



Source: prepared by the author (2024).

The back of the heated table consists only of the installation of the temperature sensor as shown in Figure 46. In the first installation, the lowest cost was chosen, using acetic silicone for high temperatures, easily found in hardware stores, but it was not effective. It was then opted for the use of Kapton tape, a special tape composed of polyamide for high temperatures above 180 degrees, where the fixation of the sensor was quick and successful.

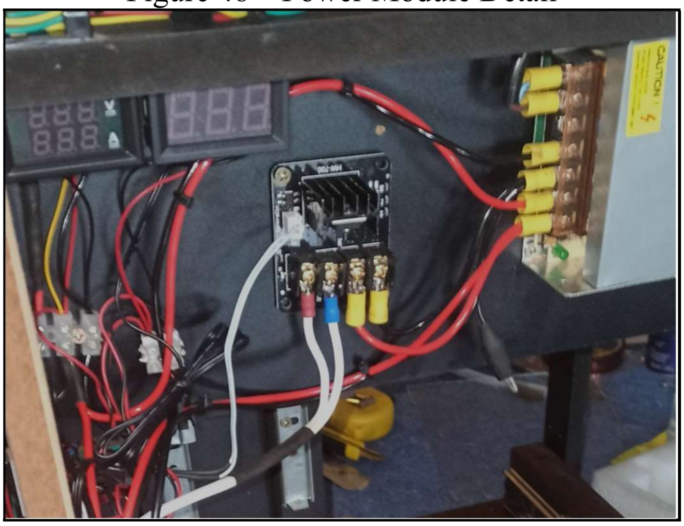
Figure 47 - Power Module Installation



Source: prepared by the author (2024).

All power supply cables in the project were soldered and connection terminals were used at their ends, as shown in Figure 47.

Figure 48 – Power Module Detail



Source: prepared by the author (2024).

The choice to use a separate power module from the Ramps board (RepRap Contributors, 2024) was due to reports in blogs that the board gets too hot due to the high current consumed by the heated table and the fact that the quality of the components is superior. The Mosfet component used is the 210A model HA210N06 supports a maximum current of 25A and a voltage of 12 to 24 volts, that is, more than enough for the demand of 11A and 12 volts of the heated table of the prototype.

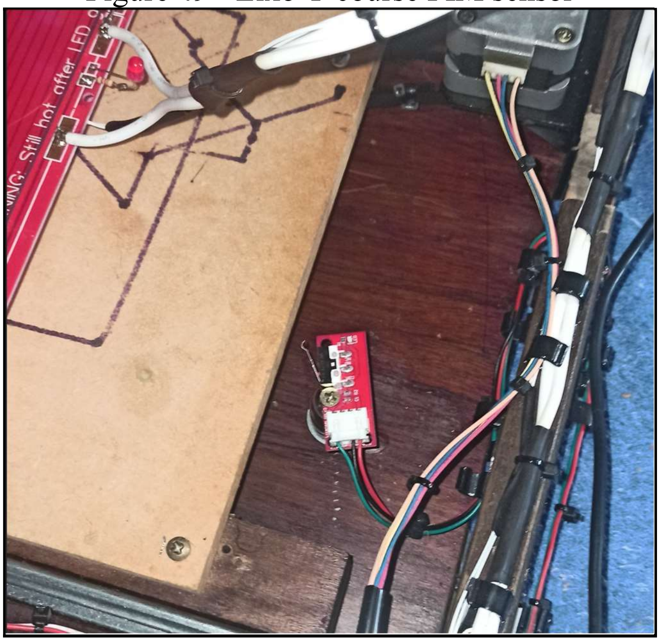
In Figure 48, you can see the connection of the power module, which at the input receives the positive and negative cable from the 12-volt source in the thickness of 2.5 mm and at the output 2.5 mm silicone cables that go to the heated table, and finally, the driver cable, which is connected to the D8 output of the Ramps board (RepRap Contributors, 2024), which is the output to the heated table, which in this configuration, serves only to activate an auxiliary power source.

This power module already comes with an active heat sink that prevents the component from overheating, due to the long working time of a 3D print that can take several hours.

3.3.6 Configuring the Limit Switches

End-of-course sensors are essential for the printer to do homming, that is, when it receives the command to go to the origin, it becomes necessary to use sensors on each axis for the firmware to identify the starting points. The limit switches, as shown in Figure 49, serve this purpose and in this project each axis had its sensor installed at strategic points.

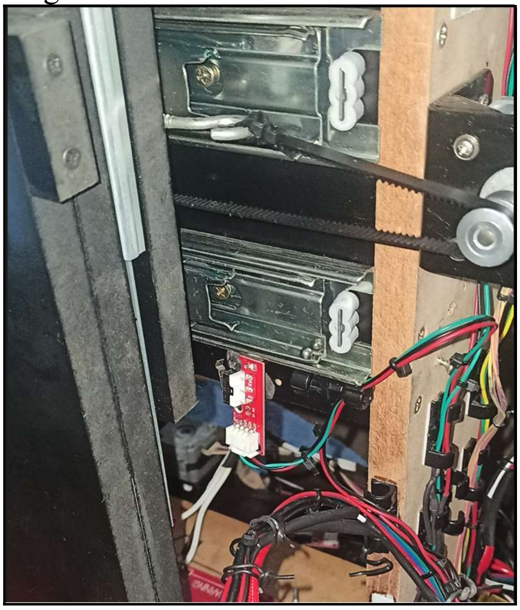
Figure 49 - Eixo Y course FIM sensor



Source: prepared by the author (2024).

Figure 49 shows the Y-axis limit switch, which was attached directly to the base of the printer with spacers to be at the height of the heated bed base.

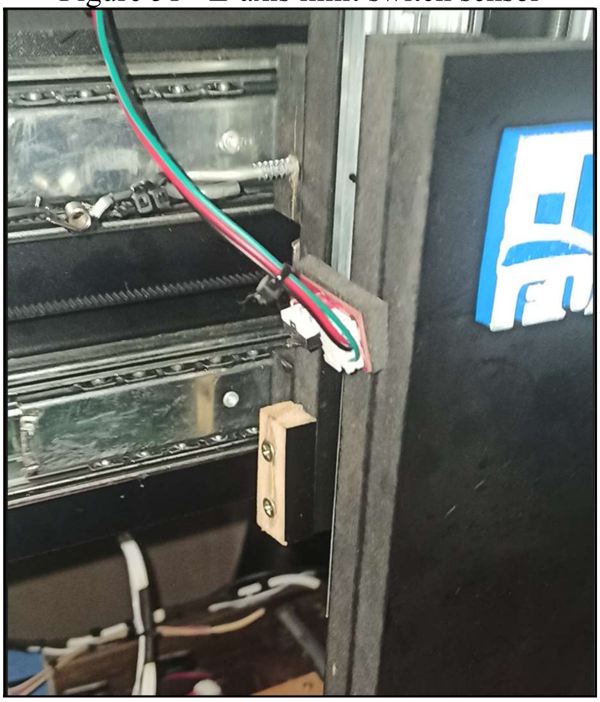
Figure 50 - X-axis limit switch sensor



Source: prepared by the author (2024).

The X-axis limit switch, as illustrated in Figure 50, was installed near the slides and is driven with the Z-axis print carriage.

Figure 51 - Z-axis limit switch sensor

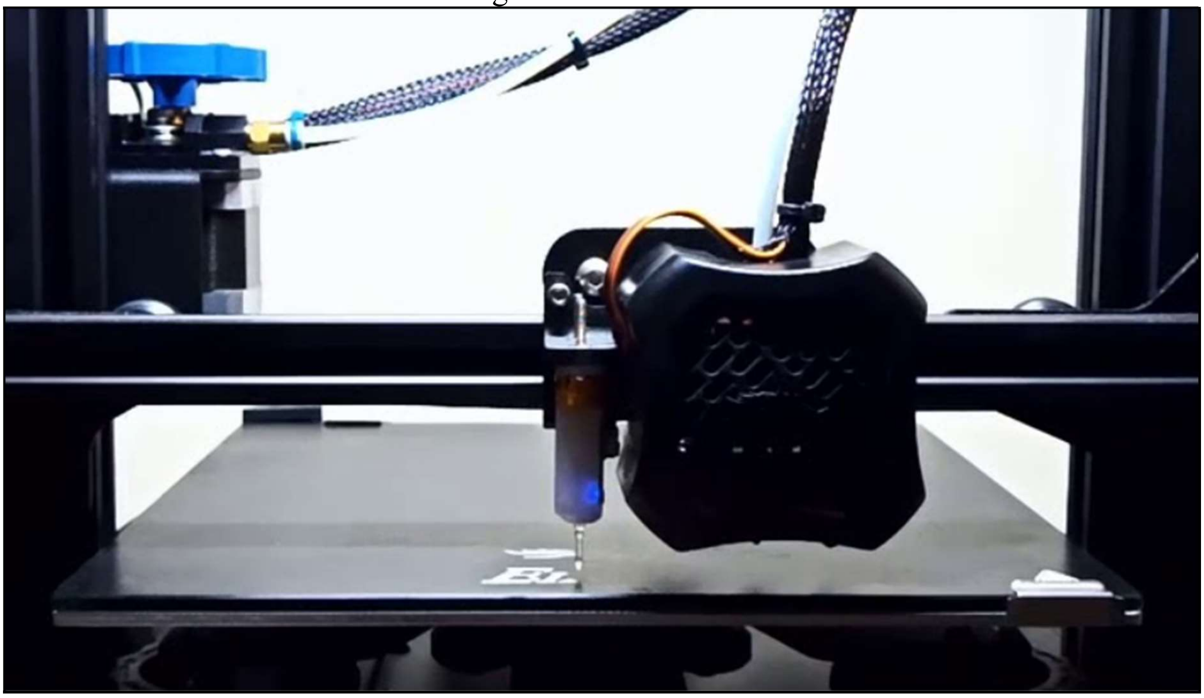


Source: prepared by the author (2024).

The Z-axis limit switch sensor is the most complex and most important sensor in the prototype. As can be seen in Figure 51, it was fixed to the moving part of the shaft and its activation occurs when the print head is fully aligned with the heated table. It has adjustment to be approximately 0.75 mm of the glass of the heated bed and it is very important, every time the printer is prepared for printing, it starts in the correct position for the filament extrusion to effectively adhere to the surface of the heated bed.

The author understands the positioning of the sensor in this location as an innovation, as there are automatic leveling accessories on the market that serve exactly this purpose, such as the BLTouch device, illustrated in Figure 52.

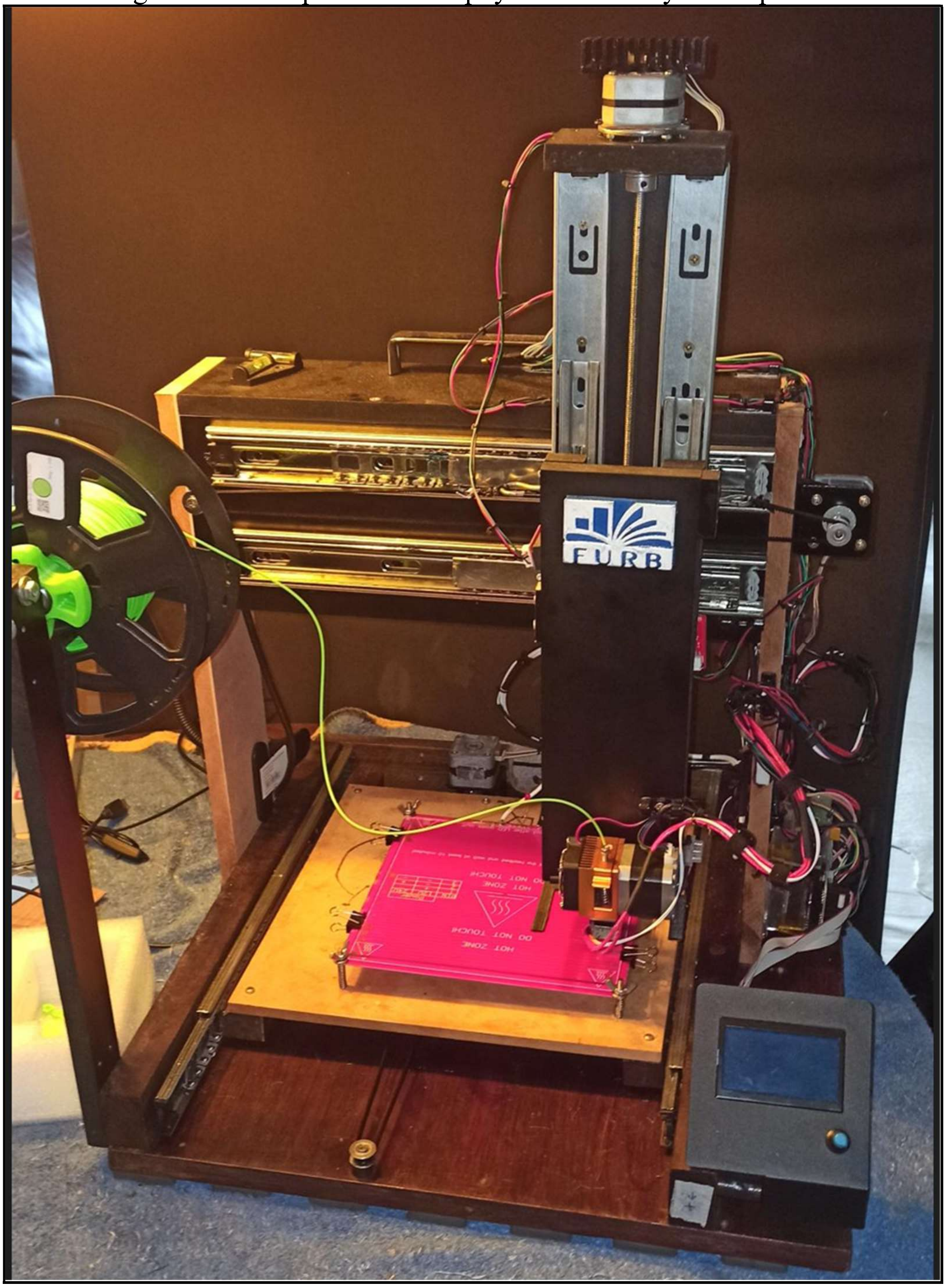
Figure 52 - BLTouch



Source: Risco-Castillo (2023).

This sensor is composed of a servo motor, which at the time of aligning the table, is activated to measure the distance and inclination of the printing nozzle in relation to the heated table, at various points on the table, in order to assist in leveling. An important piece of information is that the use of these sensors does not leave the manual leveling of the heated table optional. This functionality can be understood as a facility that occurs at the time of homming, which is understood as a command for the X, Y and Z axes to return to their initial point of origin.

Figure 53 - Completion of the physical assembly of the printer



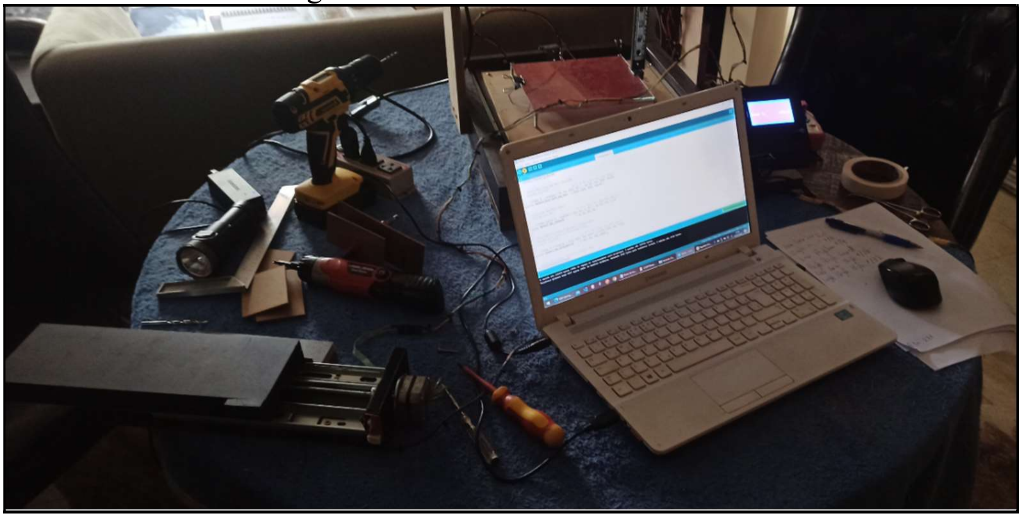
Source: prepared by the author (2024).

Finally, Figure 53shows the completion of the printer assembly with all the parts installed and connected. The next phase will be the testing stage with configuration via software and calibration of components.

The commands for moving the axes and preheating the heated table and extruder can be done via LCD display or via software. In this step, the options of the firmware itself were used via LCD display for the ease of operation during repetitive tests.

3.3.7 Z-axis calibration

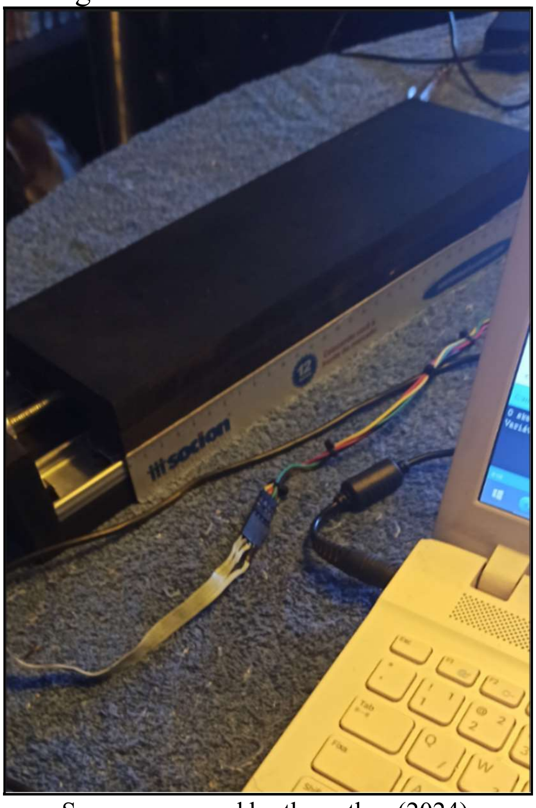
Figure 54 - Z-axis motor calibration



Source: prepared by the author (2024).

The printer components had to be assembled and disassembled several times due to maintenance and adjustments. An example of this situation can be seen in Figure 54, with the calibration and adjustments of the Z-axis advance, which is the most complex in the system. With the firmware in operational condition, at this stage the adjustments of the engine stroke advance were made, limit start test in order to avoid locking of the threaded bar due to the angle of operation.

Figure 55 - Z-axis feed calibration



Source: prepared by the author (2024).

At this stage, the movement of the motor stroke was also adjusted through the options of the LCD display. The technique consists of issuing a command for the axis to move 10 mm and the result is compared with a ruler, in order to align the values, as shown in Figure 55. When there is a difference in values between the software and the hardware, the DEFAULT_AXIS_STEPS_PER_UNIT parameter is adjusted in the source code and the firmware must be recompiled and reloaded into the microcontroller. For example, the parameter comes with an initial setting `{80, 80, 80, 80}` and defines the number of steps required in millimeters for respectively the X, Y, Z and E0 (Extruder) axes. After issuing the movement command via software, the movement result is physically compared and the parameter is adjusted through the proportional rule of three. An example is to test if with a value of 80 it has gone 0.2 mm, the value is changed to 400 and a new round is made, until it reaches the point that when executing command via software for the axis to walk 10 mm, the axis physically walks 10 mm.

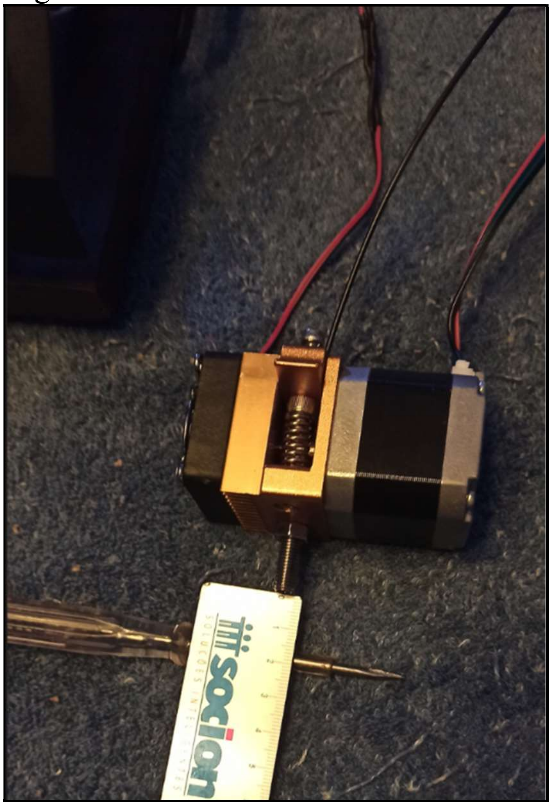
After this alignment, it is recommended to test with larger variations, such as 50 or 70 mm, due to precision and roundness. The command for 10 mm may be correct and aligned, but there may be variation in larger sizes and adjustment is necessary in all axes, because it ensures that if a 20 mm x 20 mm x 20 mm object is printed via software, it will be with this dimension that the printer will generate the part in physical form. This technique applies only to the X, Y, and Z axes. Extruder calibration is approached with a different technique.

3.3.8 Extruder calibration and X, Y and Z axes

The calibration of extruder motor steps aims to control the flow of filament that will be pulled during printing. It is mandatory for correct operation that if the software sends 10 mm of filament, the extruder has to pull exactly that amount. If you pull less or more filament than expected, deformations of various types may occur in the part, such as melted filament leakage, printing nozzle clogging, among other situations.

The technique is similar to that of the X, Y and Z axes, but the extruder must be disassembled, removing the Hotend and printing nozzle, to measure the flow with the filament without resistance. After being disassembled, as shown in Figure 56, a 10 mm traction command is sent via software and the result must be analyzed and, if necessary, adjust the DEFAULT_AXIS_STEPS_PER_UNIT parameter until the desired alignment is reached.

Figure 56 - Extruder Advance Calibration



Source: prepared by the author (2024).

After this first adjustment, a new command of 50 to 70 mm must be made to analyze the result until the desired alignment is reached.

3.3.9 Calibration of extruder heating and heated table

The heated bed (Hotbed) aims to keep the part being printed fixed through heat on a flat surface. The table used in this prototype is an MK2 table, composed of phenolite and basically it is a resistance that when it receives energy, starts to heat up due to the flow of current that circulates in its tracks.

Temperature control is done through a temperature sensor installed under the plate that controls the temperature in a way that simulates a thermostat. For example, if in the print plan, it is configured for the table to operate at 60 degrees, the resistance will be activated until it reaches 60 degrees and then it will be turned off, in a cyclic process.

When the temperature sensor reads 59 degrees, the firmware turns the heating element back on until it takes another reading and reaches 60 degrees again. An important point to note is that the firmware had the THERMAL_PROTECTION_BED_HYSTERESIS parameter changed from 2 to 4 degrees of variation due to not activating thermal protection when there is thermal variation of only 2 degrees. This thermal protection control is activated when there is a variation greater than the established limit, for example, leaving the printer operating for hours and a sensor stops operating, causing the loss of control and as a consequence leaving the resistance activated interruptedly and causing a fire. Another relevant issue is the fact that heated tables are composed to refract heat and are very sensitive to the external environment, such as wind currents, air conditioning or sudden weather variations in the environment. During the tests, as shown in Figure 57, a simple blow already causes a variation of 2 degrees at its base.

Figure 57 - Table heating test

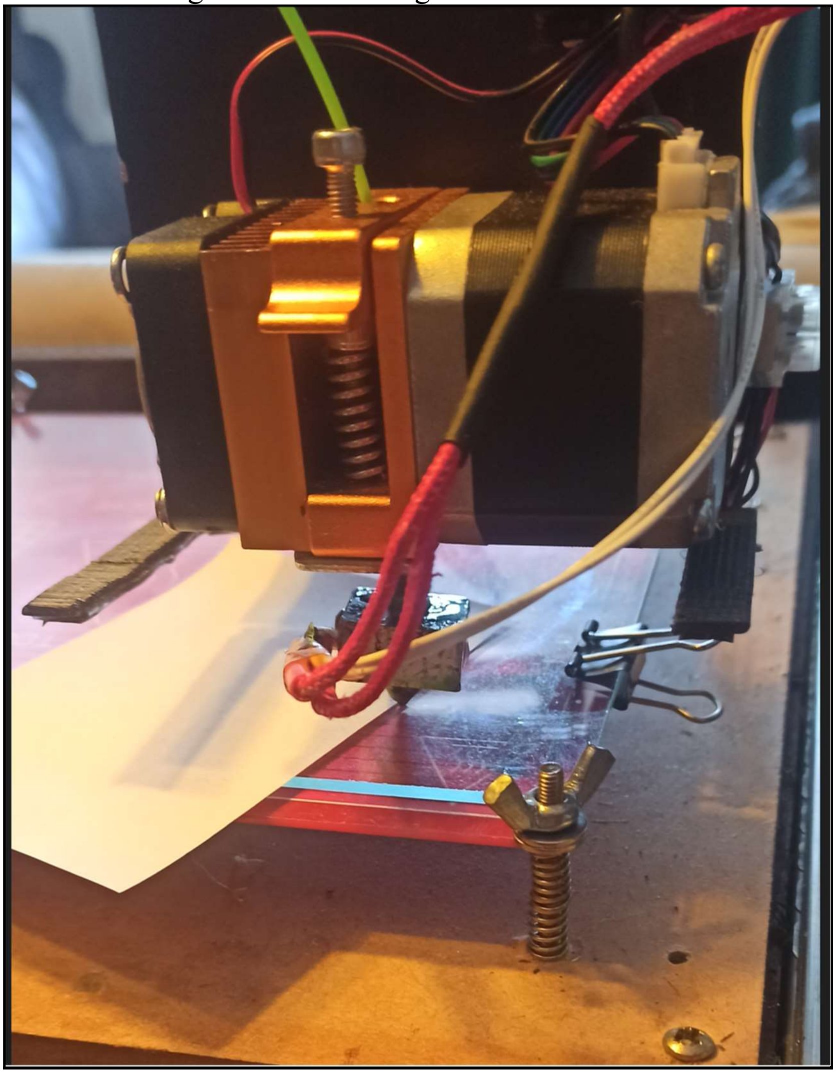
Source: prepared by the author (2024).

After these settings, the PLA table preheating routine was activated, which has a default table value of 60 degrees, as shown in Figure 57, via LCD display. The heating test of the extruder was carried out with the same technique and occurred without major problems.

3.3.10 Leveling the heated table base

This procedure consists of flattening the flatbed that must be at a perfect angle of 180 degrees at all ends of the X and Y axis. The flattening technique consists of measuring the distance between the glass that is on the heated bed and the printing nozzle. The instrument used to perform this measurement is an A4 sheet of paper with a weight of 0.75 mm, and after adjustment, the paper must be scraped between the printing nozzle and the base of the table. When the paper passes easily between the nozzle and the base without scraping, it becomes necessary to tighten the leveling screws, as shown in Figure 58.

Figure 58 – Leveling of the heated table



Source: prepared by the author (2024).

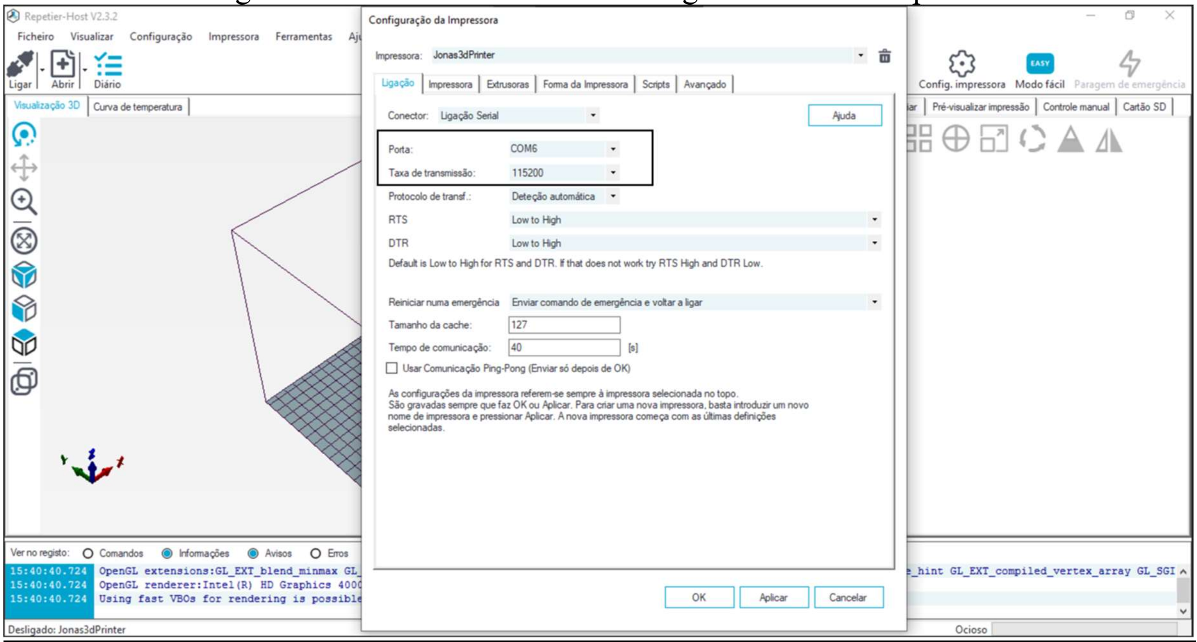
This procedure is performed in the 4 corners of the printing table and is essential for the correct functioning of the print and for the filament to be able to adhere perfectly to the glass that is under the heated bed. If it has too much slack, the filament will peel off and if it is too tight, the print head will scrape and deform the print, due to the heated nozzle melting an already printed layer. This procedure is required before all printing begins.

It is also recommended before each printing, to remove the glass for cleaning with water and neutral soap and drying should be carried out with a napkin without touching the glass directly with your fingers, in order to avoid grease and other impurities.

3.3.11 Slicer Software Configuration

The 3D printing management software used in this study was Repetier Host (Repetier, 2024), version 2.3.2, for the reason that it is free software and for the simplicity of operation. The installation took place on the Windows version 10 operating system in a clear and intuitive way, as illustrated in Figure 59, without the need for specific configurations.

Figure 59 - Printer Connection Configuration in the Repeater



Source: prepared by the author (2024).

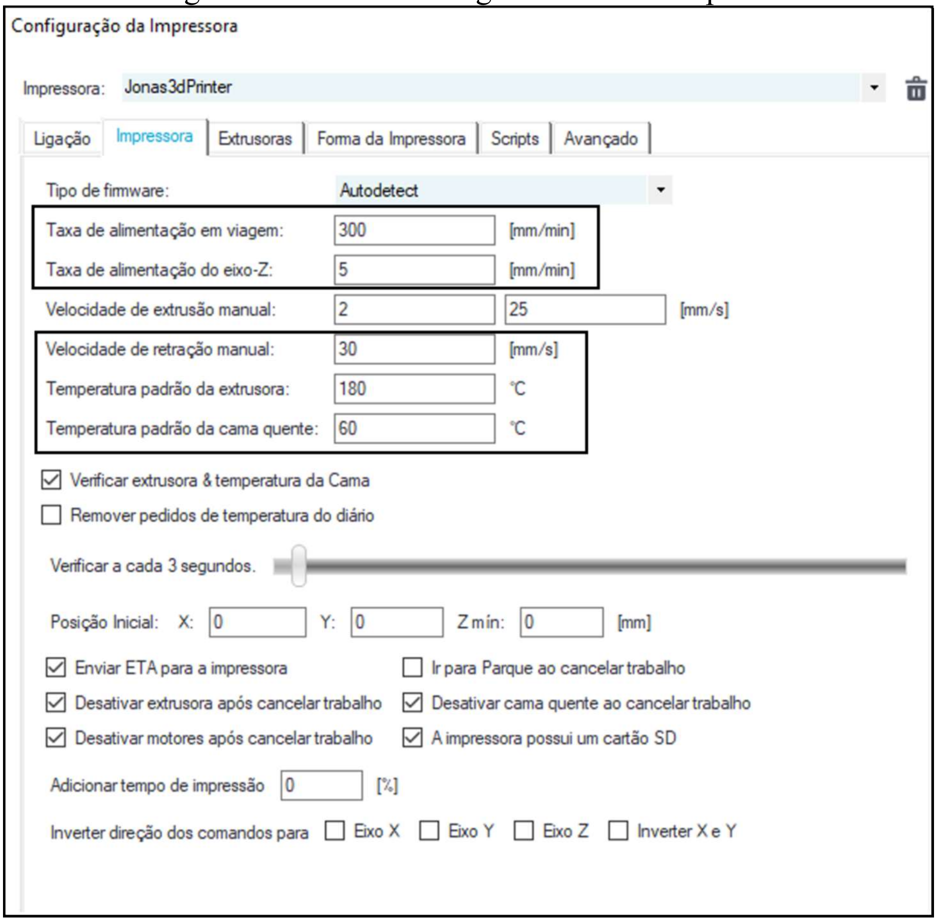
After the software is installed and running, the first point to highlight is the configuration of the serial link port speed of the microcontroller of the Arduino Mega 2560 board and this option is accessed through the Printer `Configuration > Configuration menu`.

The configuration of the Arduino board is automatically performed by the Windows operating system when connecting the board through the USB port. It is usually allocated on the COM3, COM4, COM5, or COM6 communication ports. The configuration of the software communication port must be the same port that the Arduino board was detected and is configured in the operating system, as shown in Figure 59

Another parameter to be configured is the baud rate, which in the case of this study, was configured to operate at a speed of 115200 bps. There are options for higher speeds, but in the tests performed, there were transmission problems that resulted in communication errors. An important point to highlight is that in the firmware configurations it is also configured to operate at this 115200 baud rate, through the `BAUDRATE parameter`, described in Chart 3.

.

Figure 60 - Printer Configuration in the Repetier



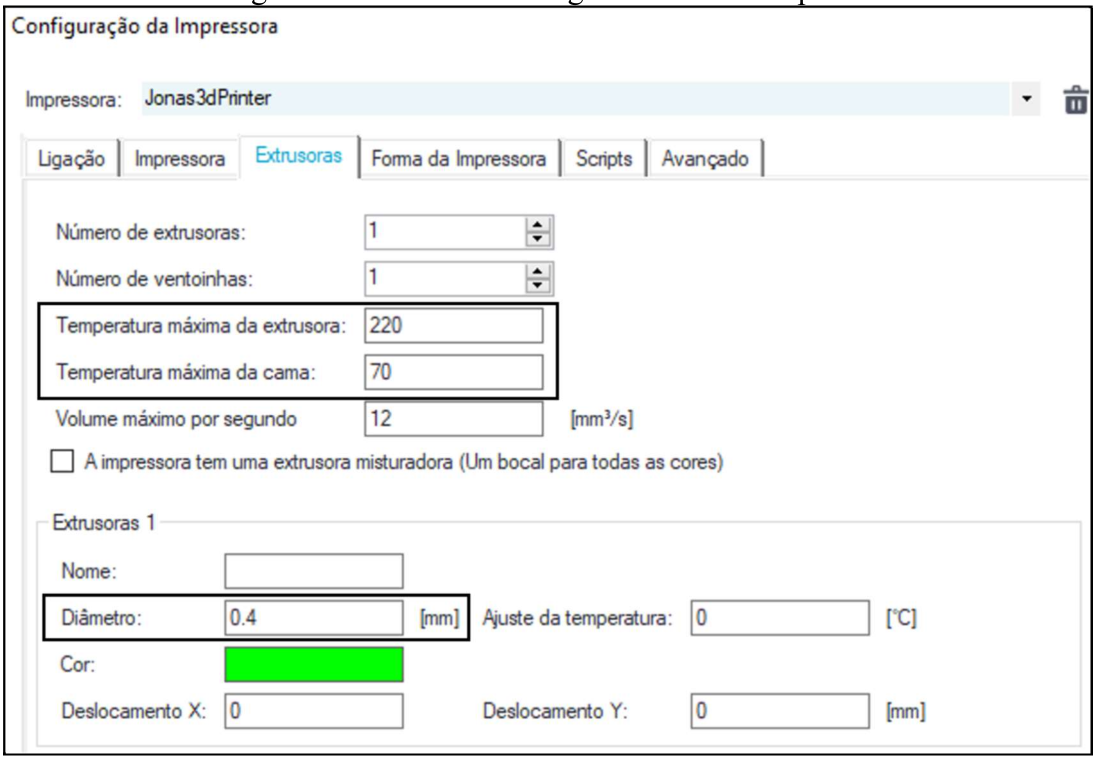
Source: prepared by the author (2024).

The second configuration, as shown Figure 60, is in the definition of the firmware type, which was kept the default value, but there was a change in the parameter of the printer's travel rate, which was changed from 3000 mm/min to 300 mm/min. This became necessary to prevent the engines from stalling at high travel speeds. The travel rate is understood as the period that the printer is not printing, but the axes are in transit in travel, that is, when accessed by the homming function, which consists of returning the axes to the initial position.

The default manual retraction speed has been changed to 30 mm/s as standard. Retraction will be addressed later in the printing tests of organic objects, but as a brief explanation, it is understood when the printing nozzle is in the air and retracts the filament until it reaches another printing point to carry out the extrusion again.

The standard temperature of the extruder was set to 180 degrees Celsius, which is the standard recommended by the PLA filament model used in the study, but varies by manufacturer. This same situation goes for the next parameter, which is the default temperature of the hot bed, has been changed to 60 degrees Celsius. The other parameters of this tab have not been changed.

Figure 61 - Extruder Configuration in the Repetier



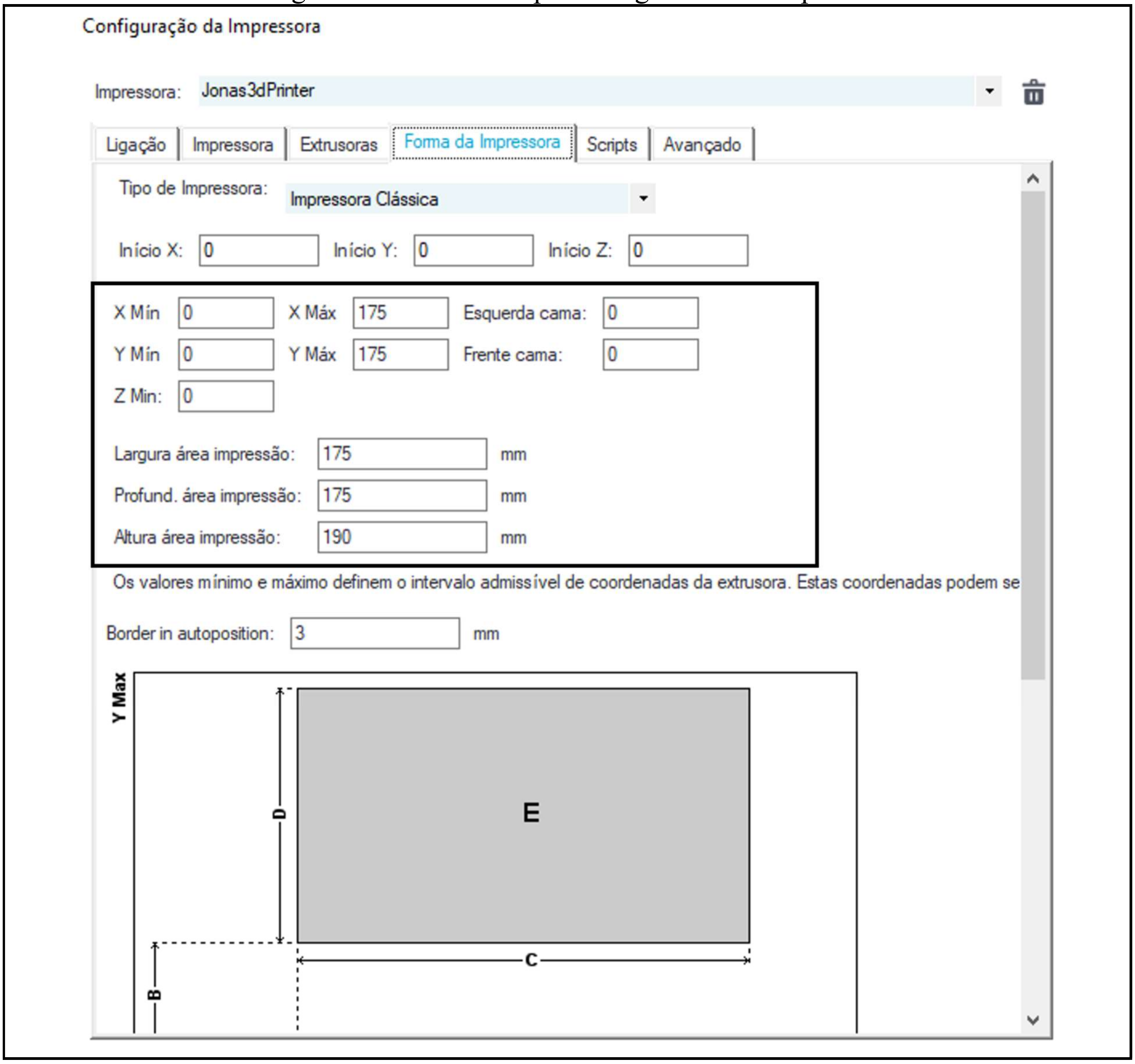
Source: prepared by the author (2024).

The `Extruders tab` contains the basic extruder settings and in the case of this prototype contains only one extruder. Figure 61 shows the configuration of the maximum temperature parameter of the extruder, which aims to control the temperature through the software and was configured at 220 degrees Celsius. This configuration enables the extruder to operate via software with PLA and ABS filaments, which has a higher melting temperature than PLA.

The maximum bed temperature limited by the app was set to 70 degrees Celsius. Physically, the hardware can reach up to 78 degrees Celsius depending on the temperature of the environment, but usually there is a failure or crash. The ideal value for this parameter should be 120 degrees, to follow the temperature of the extruder that was configured to operate with the ABS and PLA filament types, however with the standard architecture and specification of the components, this temperature is not possible to be reached and would require design changes to the prototype to have thermal insulation in the printing area in addition to more powerful components.

Finally, the last parameter configured was the diameter of the printing nozzle installed on the extruder and was adjusted to the value of 0.4 mm which is the thickness of the nozzle that came in the Ramps kit. This parameter is very important, because it directly influences the layers and heights of slicing and printing of the part.

Figure 62 - Printer Shape Configuration in Repetier



Source: prepared by the author (2024).

Complementing the configuration, in the "Printer Shape" tab, it became necessary to inform the slicer software of the printer's shapes. The physical size of the print bed is 200 x 200 mm, but due to heating and glass temperature issues, it was limited in the slicer software to 175 mm for the X and Y axes, as shown in Figure 62. There are butterfly-type nuts that help with leveling that also consume table space, but make manual leveling much easier. The height of the printing area was limited to 190 mm.

3.4 ANALYSIS OF THE RESULTS

This section presents the results obtained in the development of this work. The results are demonstrated through the printing of objects in 3D. In subsection 3.4.1, the printing tests and analysis of the results are presented. In subsection 3.4.2, the operationality of the implementation will be presented. Subsection 3.4.3 shows the main problems and their solutions. Finally, in subsection 3.4.4 this work is compared with the related ones.

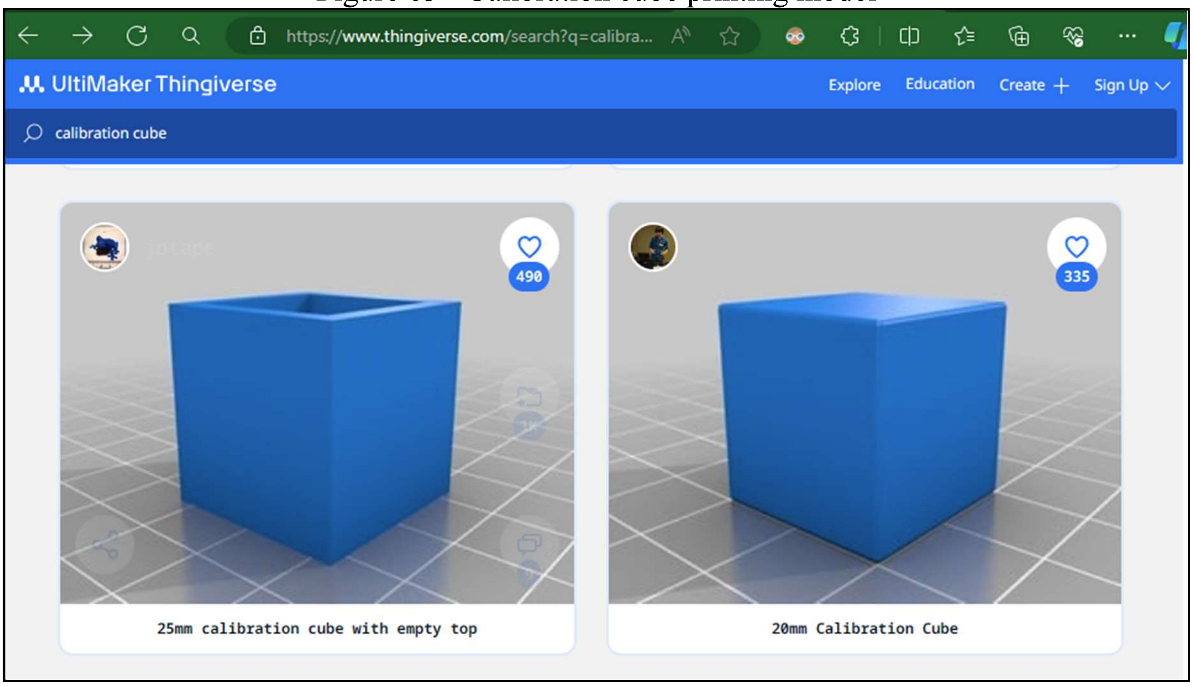
3.4.1 Testing and analysis of results

In this section, several tests will be carried out with various models of 3D objects.

3.4.1.1 20 mm calibration hub

After the basic configuration of the printer in the slicer software, it becomes necessary to choose a compatible 3D format file for printing. The 3D model to be printed was downloaded from the Thingiverse website (Thingiverse, 2024), which is a repository of 3D models for printing. The model selected for the initial tests was the calibration cube, searched for "calibration cube" and selected the option "20 mm Calibration Cube" as shown in Figure 63.

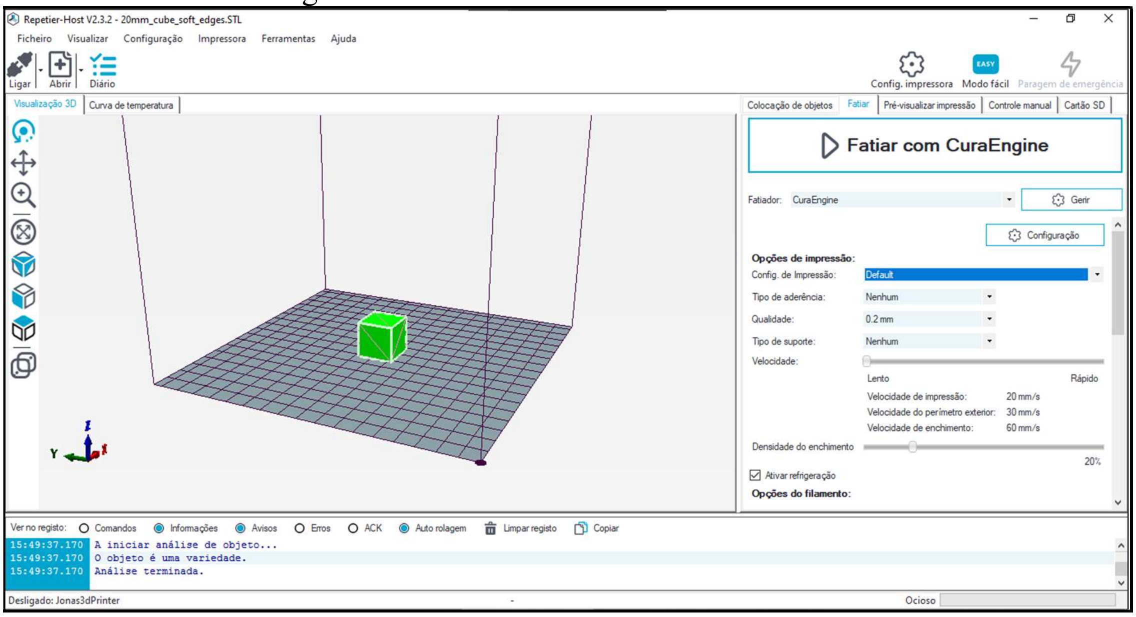
Figure 63 - Calibration cube printing model



Source: prepared by the author (2024).

After the file was downloaded and unzipped, it was opened in the Repetier Host software (Repetier, 2024). The first test took place with the software's default print settings. Figure **Erro! Autoreferência de indicador não válida.** shows the main screen of the software with the file already loaded.

Figure 64 - Main screen of the slicer software



Source: prepared by the author (2024).

The file was uploaded via the Open menu option and then the Slice tab was accessed. The first test was carried out with the default settings of the software. An important point to highlight is the print quality that was carried out in the thickness of 0.2 mm each layer. The 3D object appears in the center with a preview of what will be printed. The slicing process starts by pressing the Slice button with the CuraEngine.

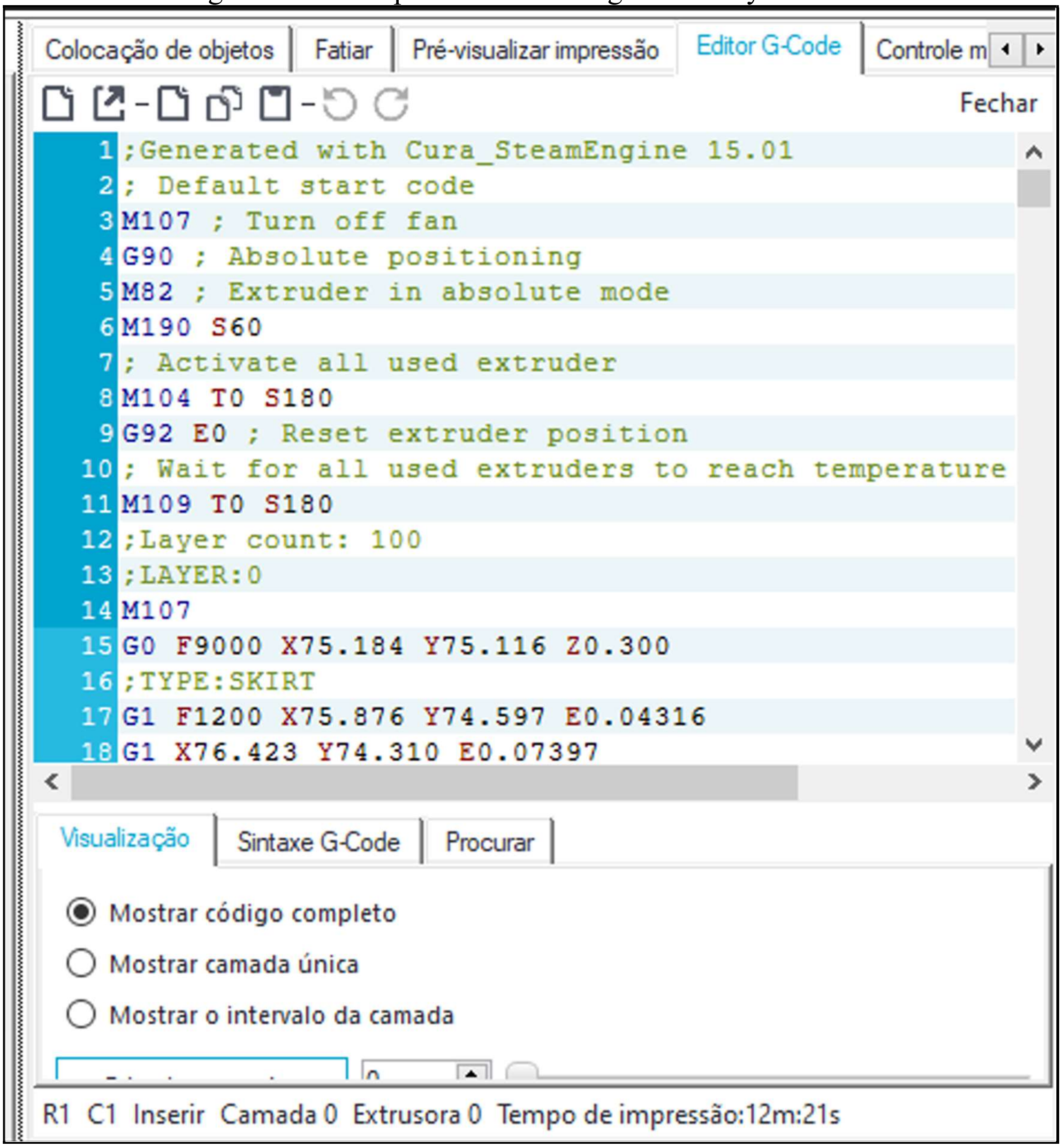
Figure 65 – 3D Printing Statistics on the Repetier

Source: prepared by the author (2024).

After slicing, the system automatically moves to the next tab, where the print preview tab is observed. In this tab, the number of layers that the 3D object was sliced is informed, in this case in 100 layers of 0.2 mm and the filament needed for printing was 991 mm, as seen in Figure 65.

The slicing process consists of reading a 3D object and generating GCode code, as shown in Figure 66, which is a script with instructions in the form of code that the *Marlin firmware* interprets the commands for the microcontroller to execute.

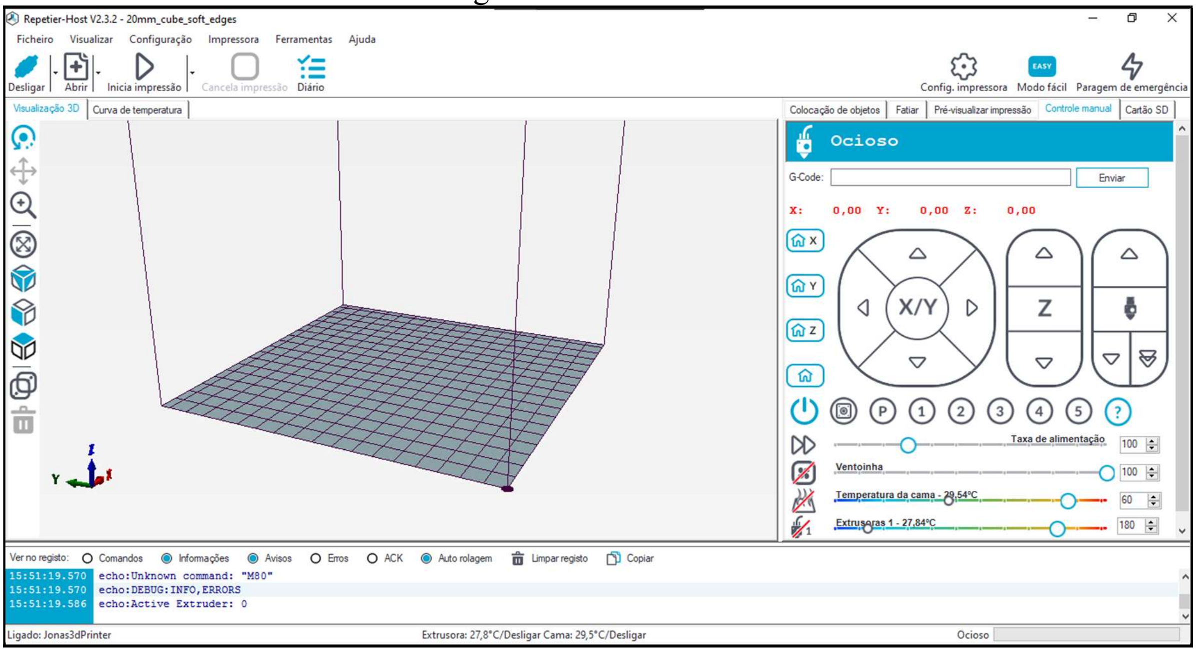
Figure 66 - Example of the GCode generated by the slicer



Source: prepared by the author (2024).

The slicing of the 3D model of this test generated a file of 8169 lines as illustrated in Figure 65 and a fragment of code from the generated script can be observed. The software allows editing of this file that is fully customizable, but it will not be addressed in this context. Figure Figure 66 illustrates the sequence of the file that the firmware will interpret, as in line 3, turn off the extruder vent, then activate all configured extruders, then start heating the table, then activate the extruder and finally start the print job. On line 17 are the coordinates to print the object's skirt. The object skirt is a type of support that the printer prints around the object in order to improve the fixation on the heated table. There are several types of object support that will not be covered at this point.

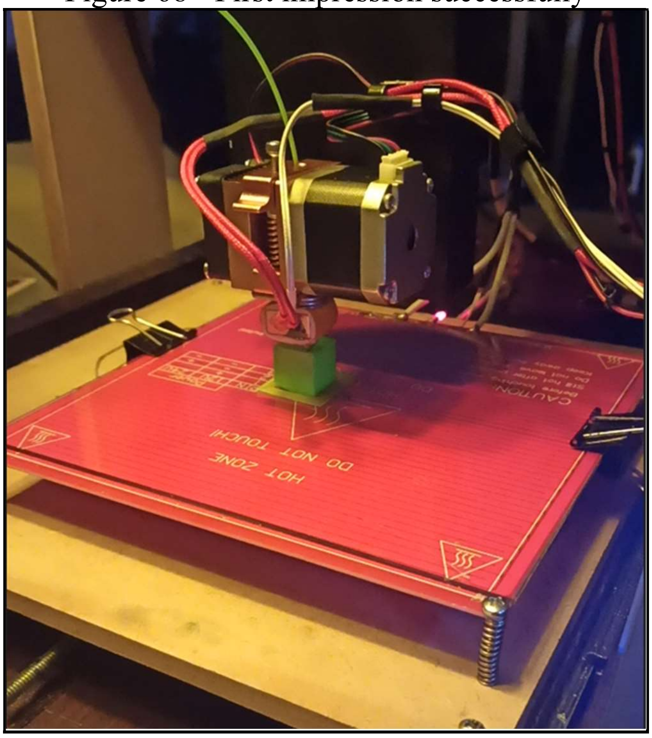
Figure 67 - Print screen



Source: prepared by the author (2024).

At this stage, the 3D object model is ready for printing after being sliced by the software and the connection to the printer must be activated by means of the `On/Off` button. Pressing the button is a command in the software that connects the printer with the *Marlin* firmware and displays the real-time job operation log at the bottom, as shown in Figure 67. The manual control tab of this image displays status information from the temperature sensors.

Figure 68 - First impression successfully



Source: prepared by the author (2024).

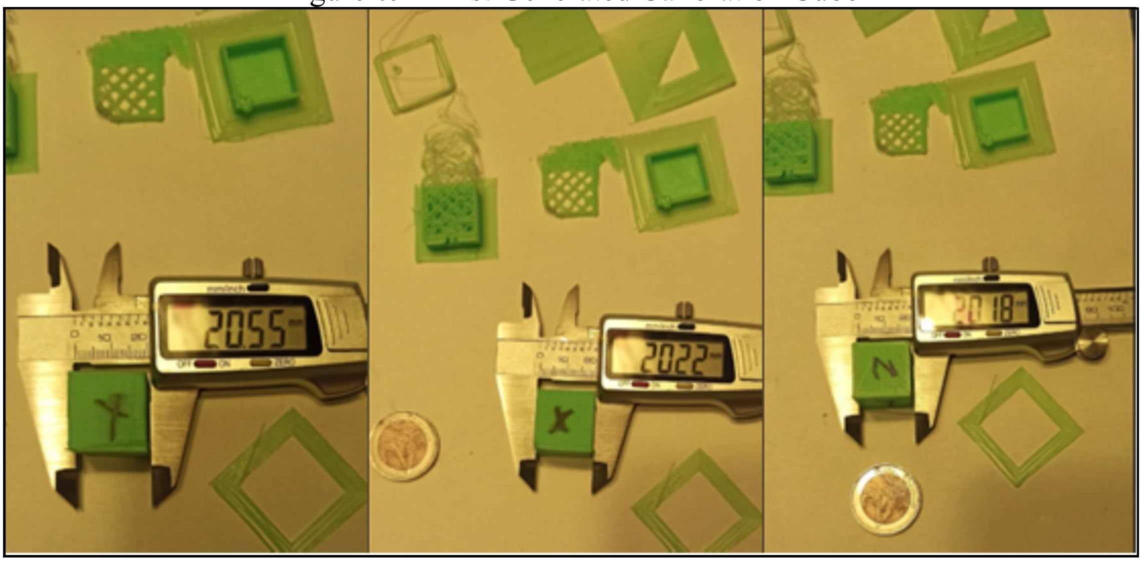
As the printing of the layers progresses, their progress is displayed in real-time on the central screen of the software. This manual control screen also allows you to move the printer's axes and call the homming command of each axis or the entire printer.

Figure At this stage, the 3D object model is ready for printing after being sliced by the software and the connection to the printer must be activated by means of the `On/Off` button. Pressing the button is a command in the software that connects the printer with the *Marlin* firmware and displays the real-time job operation log at the bottom, as shown in Figure 67. The manual control tab of this image displays status information from the temperature sensors.

Figure 68shows the first successful impression that occurred after approximately twenty attempts. During the attempts, there were adjustments to the micro alignment of the table, speed of the first layer, tightening of the belts, adjustment of the angle of the motors and other adjustments. This procedure is normal in first prints, because the printer works with heated components and is of the open type, because there is interaction with the environment, such as ambient temperature, wind and humidity of the filament.

After finishing printing, as shown in Figure 69, the result of the first calibration cube generated by the printer is observed.

Figure 69 - First Generated Calibration Cube



Source: prepared by the author (2024).

The purpose of printing the first cube was to test, adjust the basic operation of the printer and assess the calibration of the X, Y, Z and Extruder axes. As the calibration cube is 20 mm, it is understood that the calibration is correct, with a small variation in rounding after the decimal point between each axis, but only with this result, the main objective of the study has already been achieved, as illustrated in Figure 70. The filament used in this test was PLA Basic from the Brazilian manufacturer 3D Fila, with a thickness of 1.75 millimeters and with a specification of a table heated at 60 degrees Celsius and an extruder at 180 degrees Celsius. The print speed and other parameters followed the standard of the Repetier Host software (Repetier, 2024), with a resolution of 0.2 mm and an ambient temperature of approximately 28 degrees Celsius during the test. A factor that also influenced this test was the fact that all the print nozzles were clean, that is, without debris from previous prints and with few hours of printing. The filament had just been removed from the vacuum packaging and the moisture levels were at the factory standard. In this test, no adhesive product was used to assist in fixing the part to be printed.

Figure 70 - Cube generated after adjustments

Source: prepared by the author (2024).

After the initial adjustments, several cubes were generated and more complex models were explored, such as another calibration cube model called XYZ `20mm Calibration Cube`, which already contains more specific letters and grooves. The printing arrived almost perfectly in two places after the decimal point, as shown in Figure 70..

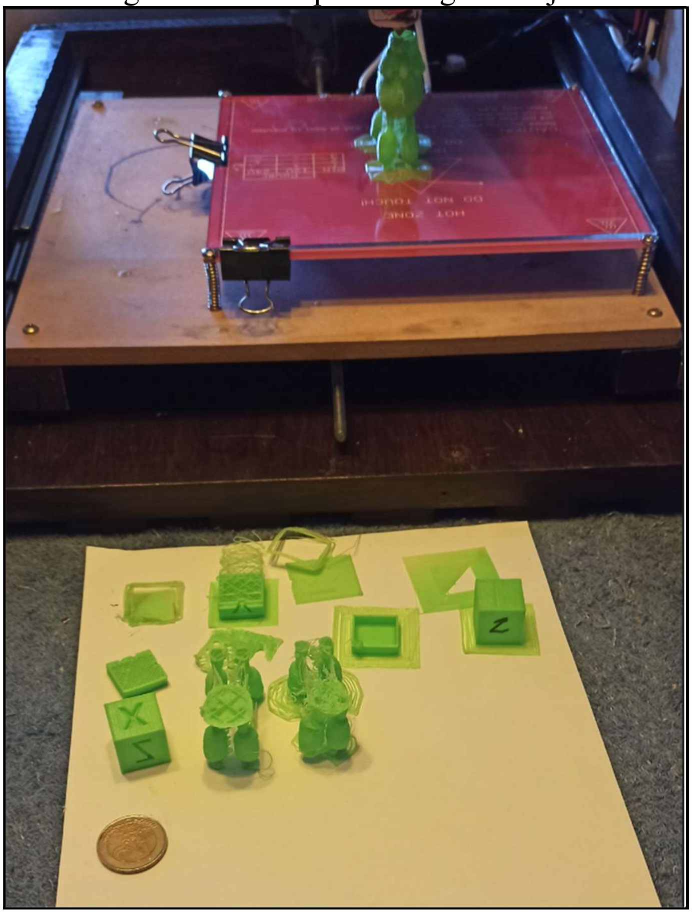
A point to highlight is that this result was achieved with components that were not designed for this purpose, for example, drawer slides that do not have the same precision as linear guided bars, specific for this type of precision operation.

At the beginning of the project, there were many doubts about the vibration of the axes when the printer abruptly changed from a Cartesian coordinate of X to Y, for example, or made a very sharp 90-degree turn, as was the case with the printing of this cube. Hinges have gaps that are natural to their structure and all these doubts were resolved with this test that proves that it is possible to use these objects for a quality impression. This calibration cube, among other objects, is used worldwide to measure and regulate any 3D printer, as it measures geometric shapes and predetermined dimensions.

3.4.1.2 Organic Object Printing with PLA

In order to further exploit the printing capabilities of the prototype, a more complex 3D object was chosen, with organic shapes that require more performance from the printer. The object chosen was an animal that has more details and can be seen in Figure 71.

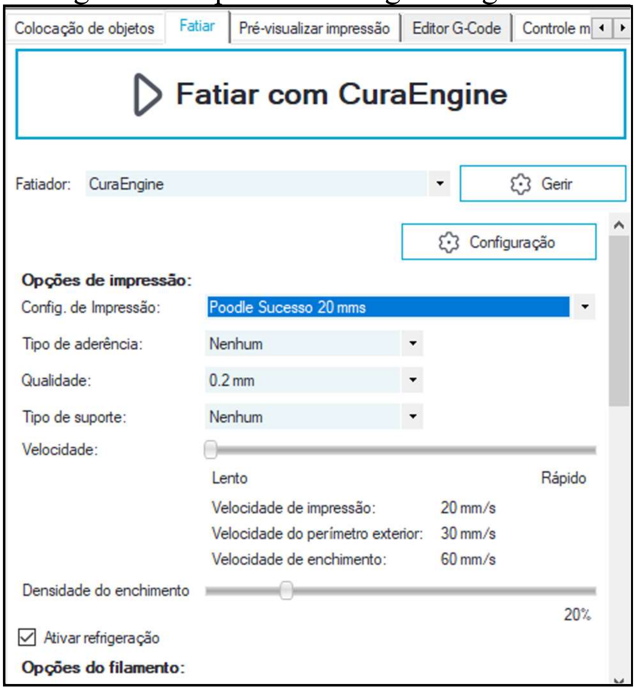
Figure 71 - First printed organic object



Source: prepared by the author (2024).

The printing of organic objects required more adjustments to the printer. New types of clearances and problems related to the fixation of the object have arisen due to the longer printing period, causing detachment of the part in some tests. It is also possible to notice the phenomenon of retraction, which occurred in this test, when printing the animal's first paw in a situation where the heated beak left a point and created a kind of web to the impression area of the animal's other paw. Another issue that was noticed was in negative angles, such as the tail and the head, which required a configuration of a support structure in the slicing.

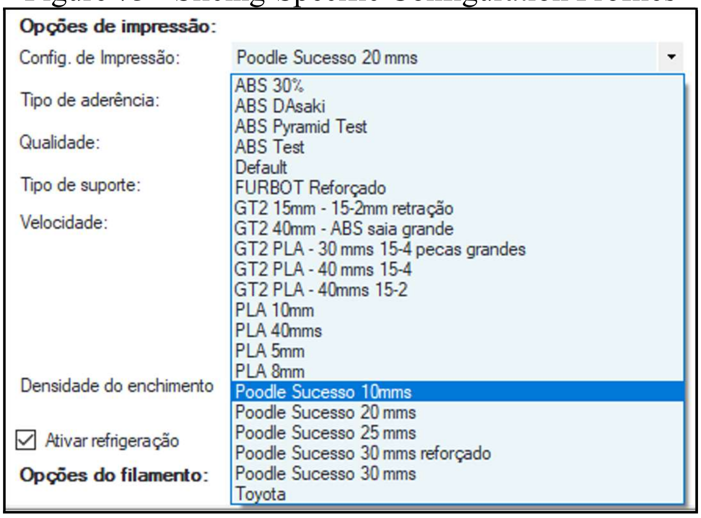
Figure 72 - Specific Slicing Configuration



Source: prepared by the author (2024).

To solve the printing particularities in the tests of an organic object, a more specific configuration at the time of slicing became necessary. In Figure 72 you can see some options such as quality, which can be from 0.1 mm, which is slower, but more precise, to 0.3 mm or 0.4 which is faster, but with less resolution, where the layers are more apparent, in the form of stairs. The printing speed influences the quality of the object to be printed, in addition to the various types of adhesion and support.

Figure 73 - Slicing-Specific Configuration Profiles

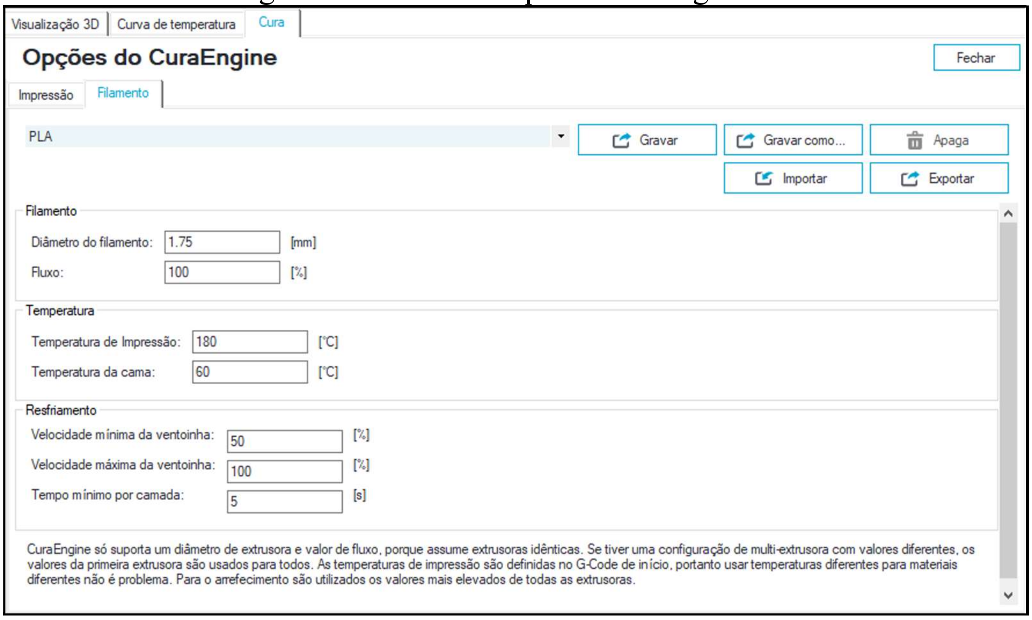


Source: prepared by the author (2024).

The software chosen for these tests was Repetier Host (Repetier, 2024) because it is simpler, but professional software such as Ultimaker Cura offers dozens of options and configurations.

As the object tests were performed, each print configuration was saved in a different profile with different combinations of variables, as can be seen in Figure 73.

Figure 74 - Filament-Specific Configuration



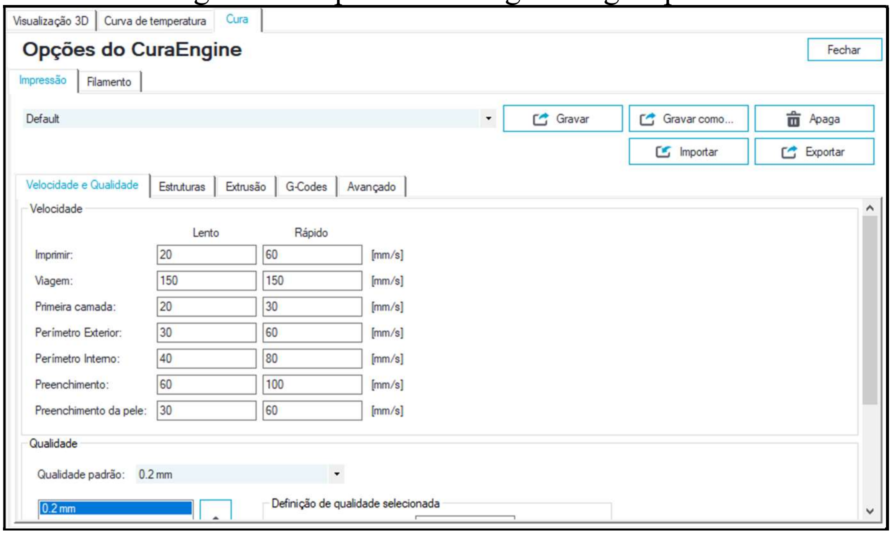
Source: prepared by the author (2024).

The slicing tab of the specific configuration contemplates issues related to the filament, such as diameter, flow, printing temperature and bed temperature, as shown in Figure 74. PLA is a very easy filament to operate and does not require many configurations in this sense, but the ABS filament, for example, demands in addition to high temperatures for extrusion and fixation, due to its characteristics of not being able to cool quickly, demands specific configurations such as fan speed control even from the extruder and has a direct influence on the quality of the part.

There are also cases of low-quality filaments, of any type or material, which even using the temperature recommended by the manufacturer, the external environment can influence, making it too soft or too hard, causing runoff, which also require configuration. These non-configurations will not be addressed in this study.

In the print tab, there is a speed setting for each printer operation that also influences the printing result, as shown in Figure 75. During the tests, it was decided to achieve quality at low speeds, such as 10 mm/s and then increase the speed, according to the success obtained from the previous printing.

Figure 75 - Specific Slicing Setting - Speed

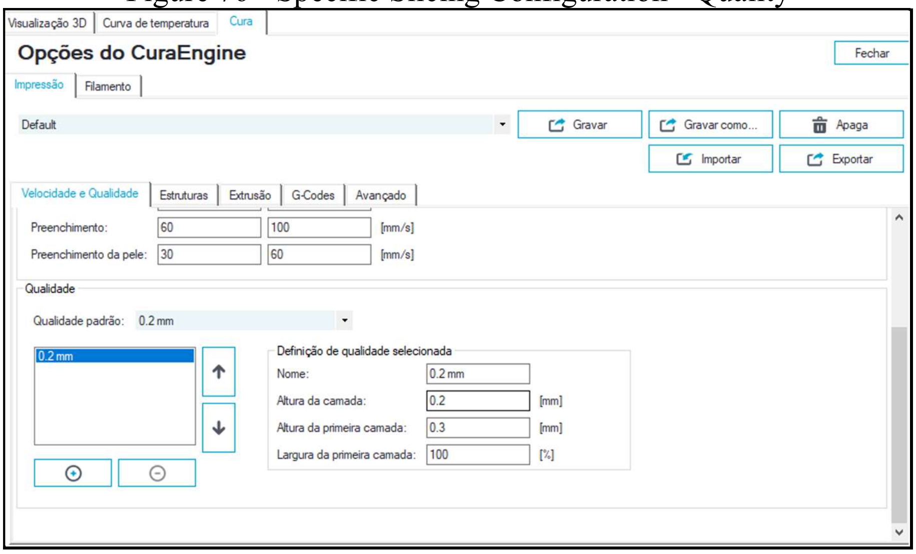


Source: prepared by the author (2024).

The speed of the first layer is one of the most important speeds during the printing process, as it directly influences the fixation of the part. In the specification of the filament, the manufacturer recommends that this speed cannot be high, because at this speed, the filament is fixed to the printing base, in this case the glass that will be hot. It also cannot be too slow, otherwise it will cause bubbles of non-extruded filament. In this study, the manufacturer's recommendation to use a maximum speed of up to 25 mm/s in the first layer was followed.

The goal of every speed setting is to achieve the highest quality in the shortest time range. As an example of this test of printing an organic object, considering a total of 329 layers, at 0.2 mm per layer, in a total of 658 mm in height, the printing took around 3 hours at an average speed of 30 mm/s.

Figure 76 - Specific Slicing Configuration - Quality

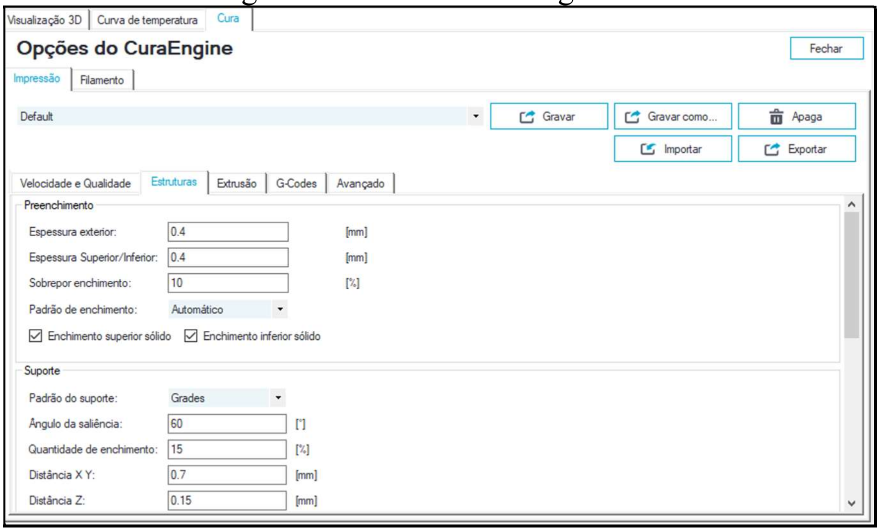


Source: prepared by the author (2024).

During the tests, in the vast majority, it was decided to operate with 0.2 mm in all layers, as it is a good quality and without variation in thickness from the first to the other layers. Figure Figure 76shows the configuration of a test performed with the first layer of 0.3 mm and the remaining layers with 0.2 mm. The objective was to create a more reinforced base in relation to the alignment of the print head with the glass with a distance of 0.75 mm.

The result of this test was not very successful, as it was found that new problems arose and it was decided to follow the tests only with a single layer of 0.2 mm.

Figure 77 - Extruder Configuration



Source: prepared by the author (2024).

The configuration of the extruder directly affects the printing speed, as it determines how many times a layer will pass through the same location. Figure Figure 77 shows the first parameters, which are exterior thickness, top/bottom thickness, and filling pattern.

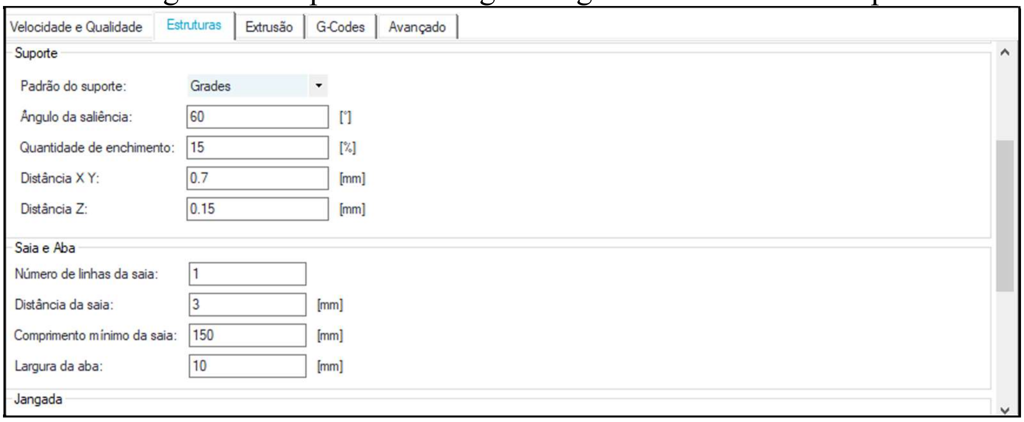
The outer thickness is understood as the configuration of the outer part of the object to be printed, in this case, being configured at 0.4 mm, the printer with a 0.4 mm nozzle will make a pass to compose this wall. The acceptable quality standard is 0.8 mm, that is, it will require two passes, but cases of 1.2 mm configuration that will require three passes in the same place were executed. A suggestion is to always use multiple values of the nozzle thickness that is being used in the printer, to avoid increasing the printing time, due to the printing nozzle working with reduced flow to reach the configured resolution.

The top and bottom thickness follow the same logic and imply the top and bottom of the printed part. For example, in this test of the organic object, you can mention the animal's tail, which has an upper and lower part, but is not the highest part of the object and in this case, it would be the head or ears.

The third important parameter is the fill overlap, which delimits the percentage that one layer will overlap the other, in order to merge the two lines of the printed layer, making the object more rigid. In the case of Figure 77, this value is very low. A quality print uses an average of 20 to 30 percent overlap.

The other configurations are support, which are used for printing objects such as Christ the Redeemer, which has open arms and the slicer software creates a kind of temporary support during printing, which makes it possible to configure the gap between the final piece and the support after printing is completed. In the case of the test with the organic object, the support was used for the part of the animal's tail and head that are printed in a gap.

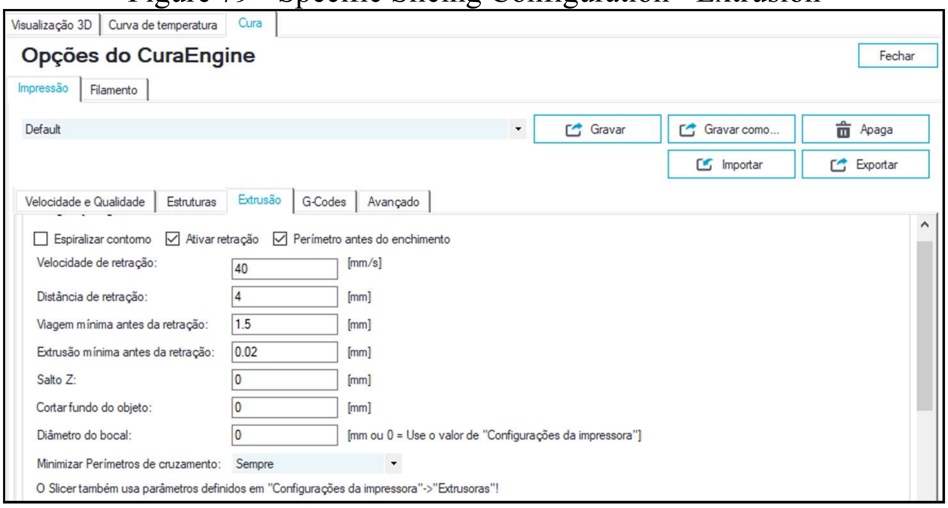
Figure 78 – Specific Slicing Configuration – Exit and Flap



Source: prepared by the author (2024).

The Skirt and Flap settings are reinforcements that the slicer software creates, to better fix the piece. In the case of the organic object being a model of an animal, it became necessary to create a skirt on each leg, to fix the piece during the entire printing process and the configurations can be seen in Figure 78. There is also the Jangada pattern, which will not be covered in this test.

Figure 79 - Specific Slicing Configuration - Extrusion



Source: prepared by the author (2024).

The extrusion configuration for the test case of this organic object became necessary to minimize the shrinkage effect of the printed object. In this case, when the layer of the animal's first leg is printed, the print head is hot and with filament inside and when moving the extruder, a kind of spider web is formed between the print regions. These settings, shown in Figure 79, vary depending on the configured print speed and retraction distance. They usually occur at the moment when the printing of a region ends, where the extruder collects the filament in order to minimize runoff and when it arrives in the next region to be printed, it returns the filament to the previous position.

This parameter also varies greatly depending on the quality of the filament, temperature, speed, among other factors. Very high values can retract the filament too much and lock the extrusion system with molten filament in the tubes. Values that are too low become inefficient to minimize the retraction effect, as shown in Figure 80. The rule is tests and more tests, for each object, until you reach a considerable result.

Figure 80 - Example of the retraction and skirt phenomenon

Source: prepared by the author (2024).

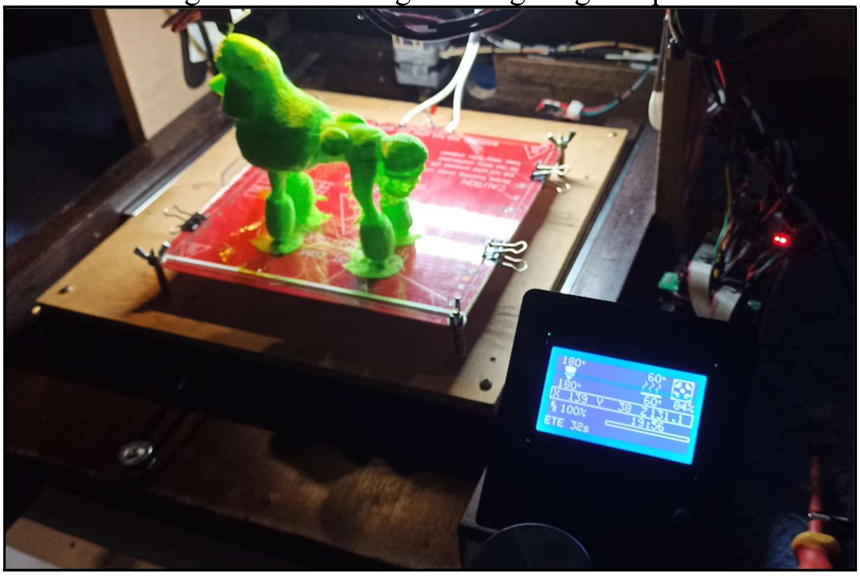
As a conclusion of this test, it can be stated that the prototype was able to successfully achieve the goal of printing an organic object through extensive configuration and combination of parameters. 3D printing differs from a traditional 2D printer, as it requires a high configuration and there is no standard configuration that is adherent to all types of objects. Each case is a specific case and requires a lot of time and dedication to achieve the expected result.

3.4.1.3 Large Organic Object Printing with PLA

The next group of prototype tests aims to print large, complex parts to test the strength of all parts and the structure of the prototype. This organic object had its scale increased by

100%, with a height of 125 mm, totaling approximately 625 layers of 0.2 mm, with optimized configuration, as shown in Figure 81.

Figure 81 - Printing of a large organic part



Source: prepared by the author (2024).

The print job took approximately 20 hours, without major problems. The only problem reported in the period was the formation of knots in the filament feeder, which was later solved with a special support for the roller, documented in this project. Figure Figure 81, at the bottom of the display, shows the exact printing time of 19 hours and 56 minutes.

Figure 82 - Evidence of the printing of a large organic part

Source: prepared by the author (2024).

As illustrated in Figure 82, evidence of the printed part with a height of close to 125 millimeters can be observed.

3.4.1.4 Paint Adhesion Test on PLA

In order to test the adhesion of paint on the PLA material, a logo was printed in low relief, as shown in Figure 83, to later submit the piece to painting using a first layer with catalyst and then to paint in two colors. This painting was carried out by a professional in label paintings from the company CCL located in the city of Blumenau, Santa Catarina.

Figure 83 - Printing of objects in low relief

Source: prepared by the author (2024).

As can be seen in **Erro! Autoreferência de indicador não válida.**, even with the dry paint, the blue paint ran off the piece, even with a catalyst and also the white paint on the top did not adhere perfectly to the piece.

Figure 84 - Evidence of object painting with PLA

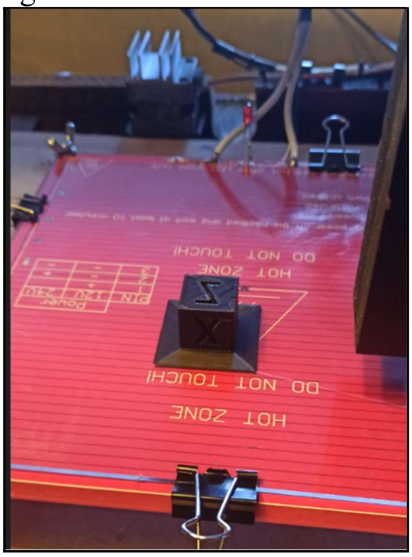
Source: prepared by the author (2024).

In this section, only a sample of the most relevant tests with the PLA material were reported. In the next session, tests that are outside the scope of this project will be aborted, but were carried out with the objective of analyzing the behavior of the ABS material, in an open printer, that is, without thermal insulation in its printing structure.

3.4.1.5 Calibration cube test with ABS material

The first test to be performed with ABS material was a 20-millimeter calibration cube, already used in the previous test, but with different material and temperatures, as shown in Figure 85. The extrusion temperature for this material was set at 220 degrees Celsius and the heated bed set at 78 degrees Celsius.

Figure 85 - ABS calibration cube



Source: prepared by the author (2024).

The temperature recommended by the manufacturer of the ABS material is 110 degrees Celsius, but due to the technical limitations of the project, the maximum temperature that the printer can maintain without locking and entering thermal protection mode was used. This protection is activated when a target temperature is set and is stable without increasing or decreasing for a predetermined time.

After several printing tests with the material, some non-conformities were found, among them, the case of the heated bed not operating at the recommended temperature and the detachment of the part from the printing base during some printings. The palliative solution for this situation was the use of liquid adhesive for 3D printing, which worked satisfactorily. Kapton tape was also used to fix the piece, in combination with the raft-type base generated by the slicer, which consists of printing a solid base similar to a raft in the entire printing space with several layers, and then starting the printing of the piece. The result of the Kapton tape with the raft proved satisfactory in some cases, but it is a very laborious process.

The most efficient solution was the use of extra-strong hairspray, applied directly to the glass in a very generous layer. An issue to mention is that in every print, the glass should be removed from the heated bed, cleaned with water and neutral soap and then dried with a napkin and avoid direct contact with the fingers. After the glass is dry, you should apply the fixative and wait about 5 minutes to then heat the table.

Another effect that happened with the ABS material was the generation of deformations between layers, such as warping of the part. This solution was partially solved by reconfiguring the table's heating system, which was changed from Bang-Bang mode to PID Tunning. The configuration of auto tune will not be addressed in this work, but there is ample detail of the configuration procedure on the internet on pages and social networks such as Youtube.

The Bang-Bang heating system of both the heated table and the extruder consists of heating the resistance at full power until it reaches the established temperature, where the system is turned off and it is activated again until it reaches the target temperature again, acting in a similar way to a thermostat.

The PID Tuning (PID) system is a more complex and more efficient process, where during the adjustment made by the firmware, a configurable amount of heating is performed both of the extruder and the heated table and control parameters are established, which keeps the system always activated intermittently, resulting in a reduction of temperature variation during the printing process and thus providing a better quality in the generated part.

Figure 86 - Evidence of calibration cube in ABS

Source: prepared by the author (2024).

After the PID fixing and adjustment adjustments, the printing result was surprising. The calibration cube was printed in 13 minutes, without deformations, with room temperature at 29 degrees Celsius, extruder at 240 degrees Celsius, table heated to 78 degrees Celsius and use of an extra-strong fastener.

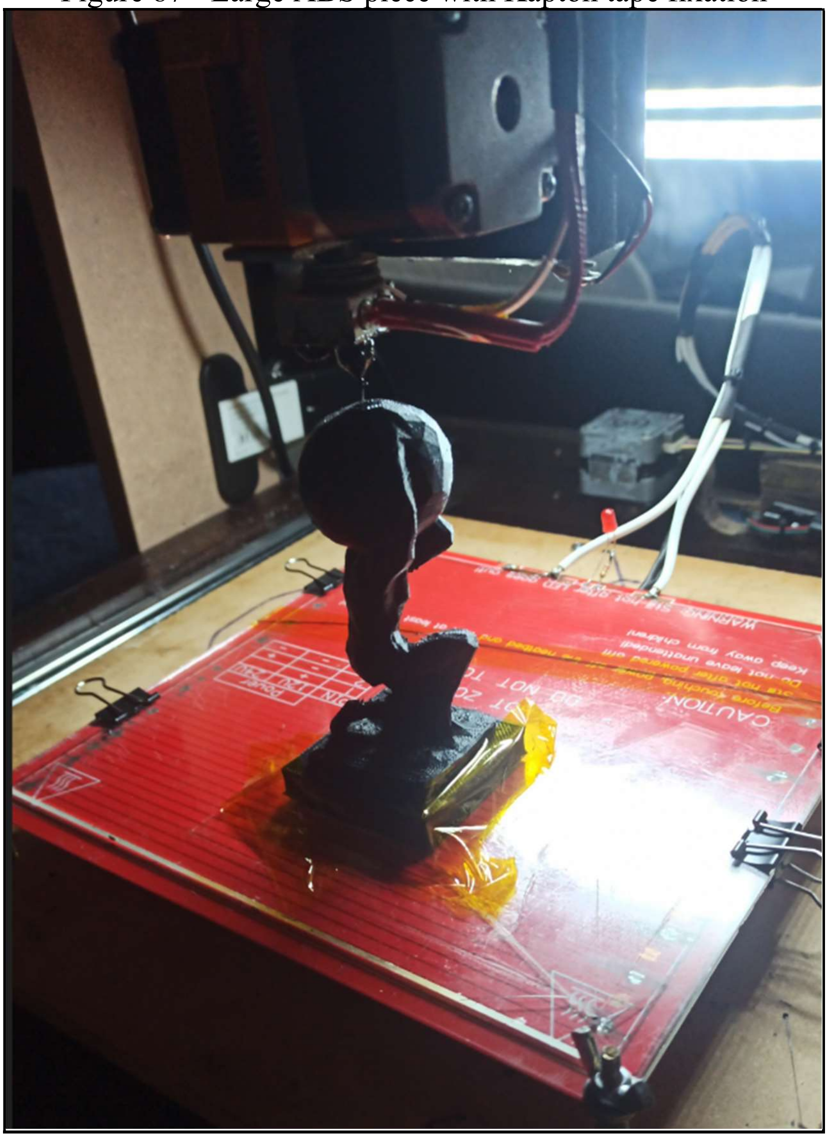
As illustrated in Figure 86, the print quality was superior to the PLA material and so was the printing accuracy. The cube reached the perfection of 20 millimeters, with two places after the decimal point, measured with a digital caliper. The configuration parameters of the motors have not changed from the test with the PLA material.

Another point to highlight is that ABS material can operate at speeds higher than PLA, maintaining quality, but it is a very sensitive material to changes in weather conditions, such as wind, cold, humidity, etc.

3.4.1.6 Large workpiece testing in ABS with auxiliary clamping

This test aims to print a large part in ABS material, as shown in Figure 87, using auxiliary fixing, in an open printer, not following the manufacturer's specification, to evaluate the result.

Figure 87 - Large ABS piece with Kapton tape fixation



Source: prepared by the author (2024).

Figure 87 shows the impression of a large object, with a combination of Kapton tape, a table heated to the limit of 78 degrees Celsius and the use of an extra-strong hair fixative applied to the glass.

Figure 88 - Large part test evidence in ABS

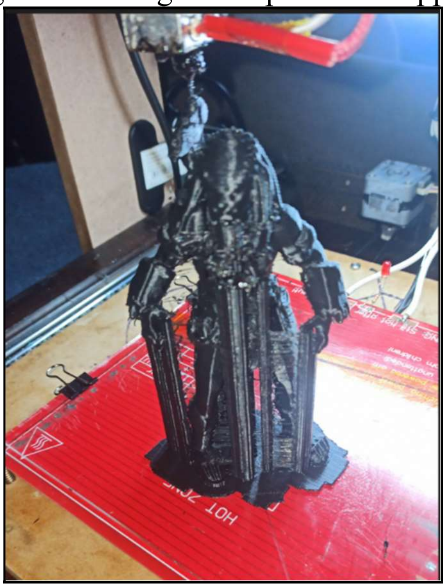
Source: prepared by the author (2024).

The evidence of the test of the part print is illustrated in Figure 88, with a resolution of 0.2 mm per layer. The base of the piece, because it contains solid shapes, a small warping appeared, which was minimized by the use of the fastener and the Kapton tape. It is worth mentioning that the printing quality of ABS on some parts is surprising.

3.4.1.7 Large part test on ABS with stand

The objective of this test is to generate a larger part with the ABS material, using the slicer's support functionality and evaluate the results, as shown in Figure 89.

Figure 89 - Large ABS part with support



Source: prepared by the author (2024).

Figure 89 shows the use of the support generation option during slicing. The supports help in the correct printing of parts where there is no direct contact with a base, as in this example, the hands, the chin, among other parts. To be successful, the support can be configured to be generated with a distance of 0.3 mm from the main part to facilitate its removal after printing is finished.

Figure 90 - Evidence of Large ABS Part with Stand

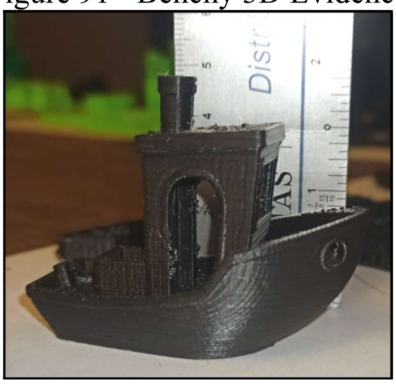
Source: prepared by the author (2024).

Figure 90 shows the finished piece, without the supports and with scraping of the filament remnants resulting from retraction. It can be mentioned that ABS filament, being harder and drying faster, generates less shrinkage than PLA material.

3.4.1.8 Resolution and stress testing of ABS printing with Benchy 3D model

The next test carried out was with the use of the 3D Benchy model, as shown in Figure 91, which is widely used to jointly perform various parameters and capabilities of a 3D printer both in symmetry, warping, resolution and protrusion. It is seen as a test to stress the entire system with difficult angles and evaluate the quality of the equipment in general.

Figure 91 - Benchy 3D Evidence



Source: prepared by the author (2024).

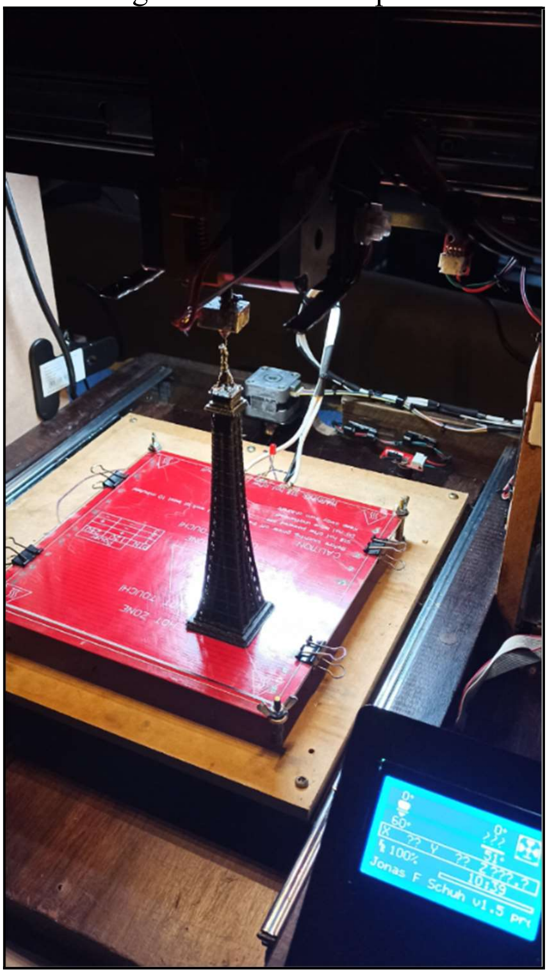
Figure 91 shows the evidence of the printed part, without any grinding, sanding or finishing adjustment.

3.4.1.9 Large Object Testing in ABS

The last test to be performed with ABS material is a large, detailed object. The example used is a 3D model of the Eiffel Tower. This model is divided into two pieces, totaling 30 centimeters in height.

The impression of both parties went smoothly. Figure 92 shows the printing of part A, totaling 16 centimeters in height, printed in ABS and lasting 10 hours and 39 minutes.

Figure 92 - ABS tall piece

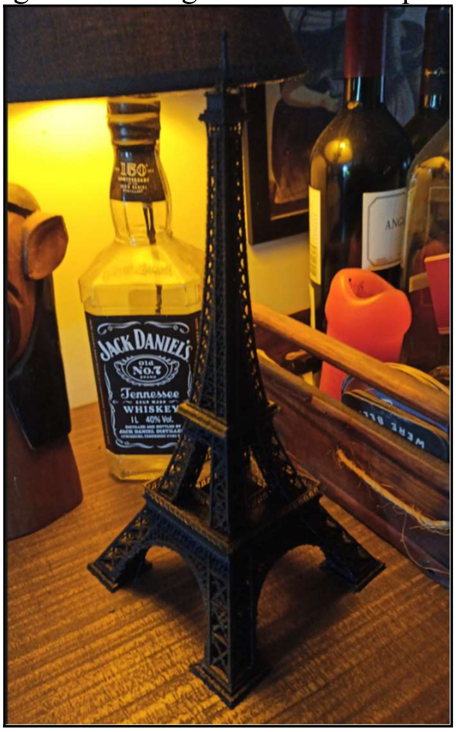


Source: prepared by the author (2024).

Figure Figure 93 shows the assembled part, totaling 30 centimeters, where parts A and B were fixed with hot glue to the ABS material that adhered very well. The total printing time of the two pieces totaled approximately 40 hours of printing. The base of the tower is 14 centimeters.

This test aimed to evaluate various behaviors and it can be concluded that printing large parts with ABS material demonstrated an excellent result. The issue of the duration of the entire printing structure, which operated for 40 hours straight, without any technical problem, both heating, shaking and finally, stress tests of axis movement due to the fact that the printing area of the base is large.

Figure 93 - Large finished ABS piece



Source: prepared by the author (2024).

Part A of the model tested the print in terms of height and movement of the Z axis, while the base of the 14 centimeter or 140 millimeter turret tested the movement capacity of the X and Y axes, using almost all the capacity of the print bed.

3.4.1.10 Completion of the tests

The tests developed in this section totaled more than 200 hours and the execution took place with different combinations of techniques, materials, weather conditions and tools. In total, more than 50 models were printed in 3D, as shown in Figure 94 evidence of the printed objects can be seen.

During the tests, a one-kilogram roll of ABS Premium material (unbranded) in black color was used, where about 80 percent of its capacity was used, and five hundred grams of the PLA Basic material from the company 3D Fila, which was used 90 percent of its totality. In this section, only the most relevant cases were exposed and commented on. The scope of print tests in its entirety contains images of characters, organic objects, mechatronics part holders, images of sights and logos.

Figure 94 - Completion of the tests

Source: prepared by the author (2024).

PLA material is much easier to work with in 3D printing than ABS material. In terms of results obtained with the prototype, both materials exceeded expectations.

The tests demonstrated extreme versatility of the PLA material both in quality and operation and the results obtained with the ABS material, considering that even used in an open printer, without reaching the ideal desktop heating temperature recommended by the manufacturer, also exceeded expectations. The only tests that ABS is not recommended in this scenario are the cases of printing rigid geometric shapes, such as a rectangle or any other shape that requires enormous fixation with the base, which after a few layers, begins to warp the printed base and twist the piece.

3.4.2 Implementation operability

In this section, the operation of the implementation will be presented through a case study. The case study selected to demonstrate the use of the solution is the main structure of the Furbot project (FURB, 2024).

The requirements to meet this demand are:

creation of a structure capable of supporting the Furbot's structure on its lower base that is light enough not to impair performance;

the dimensions of the Furbot's base measure 25 centimeters wide, 25 centimeters deep and 29 centimeters high;

Because the printing area was smaller than the intended size of a single piece, it became necessary to create several interconnected plates to build the structure;

the structure must be low-cost;

the resources used, preferably, should use the labor of the scholarship holders allocated to the Furbot project.

To meet these requirements, it was decided to start printing plates with ready-made models, through model searches on the Thingiverse website, which is a repository of 3D models (Thingiverse, 2024).

Figure Figure 95 shows the result of the first experiment, with 10 x 10 centimeter plates and their connections printed with ABS material.

Figure 95 - Plates made of ABS with 3D model

Source: prepared by the author (2024).

The results obtained from this experiment were not satisfactory, for the reason that the structure did not reach the desired rigidity, in addition to the structure being printed with the ABS material not being perfectly aligned in relation to the base, due to the warping of the material. This approach has been discarded.

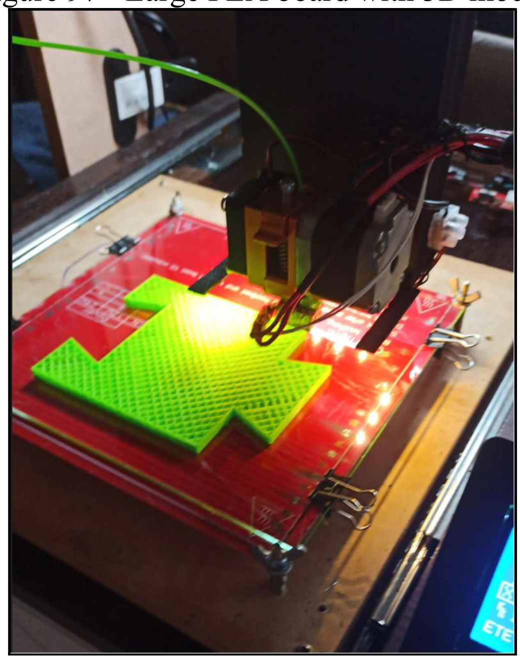
After analyzing the results, he decided together with the scholarship holder to create his own 3D model to test the solution.

Figure 96 - Plates made of PLA with their own 3D model

Source: prepared by the author (2024).

In Figure 96, it can be seen that this solution has become more efficient, due to the increase in the thickness of the plates, made possible by the PLA material that was created with perfect alignment to the base. The new plates generated in the prototype, as shown in Figure 97, measuring 10 centimeters wide, 5 centimeters deep and 1 centimeter high, solved the problem of rigidity and the connection between the plates. To achieve the perfect connection between boards, it became necessary to adjust the 3D model in the male and female fitting, reducing the male fitting by 0.2 mm. After this goal was achieved, the next goal was to generate larger plates.

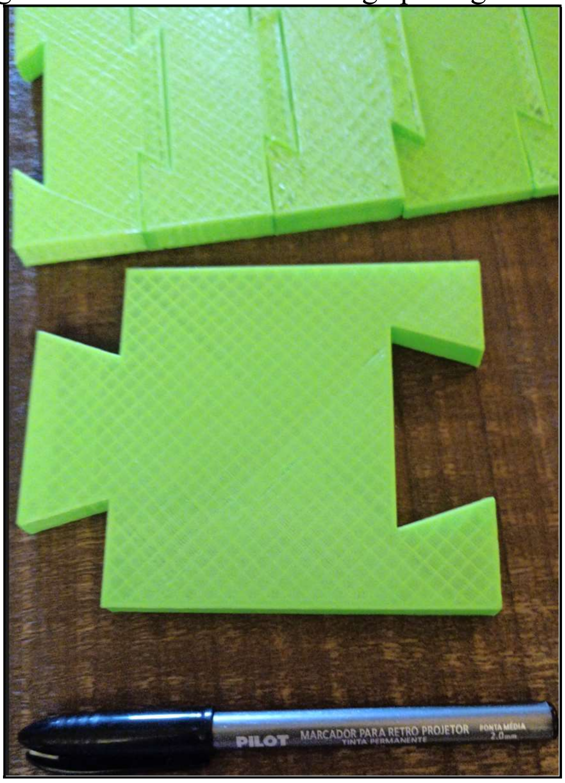
Figure 97 - Large PLA board with 3D model



Source: prepared by the author (2024).

The prototypes of the large plates were printed in the dimensions of 10 centimeters wide by 15 centimeters deep and 1 centimeter high. The printing process of each part took approximately 4 hours. Figure Figure 97 shows how the internal reinforcement structure is in the form of a grid.

Figure 98 - Evidence of the large plate generated



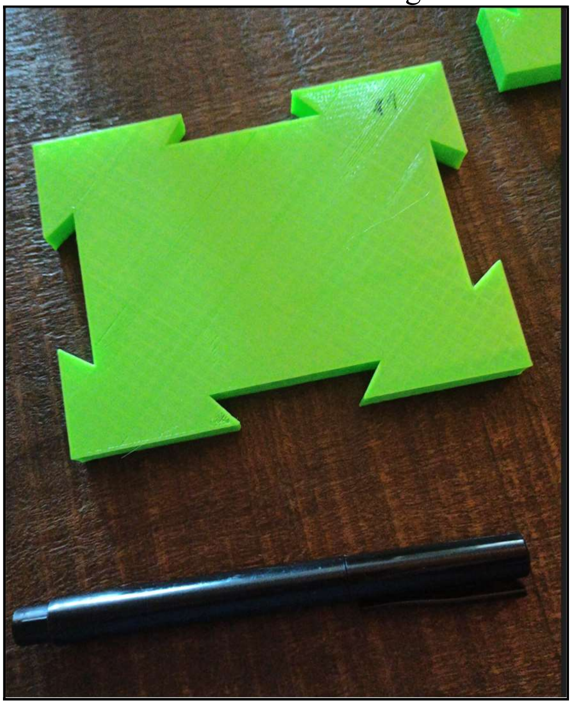
Source: prepared by the author (2024).

Figure Figure 98 shows the large plate compared to the small plates. This step demonstrates that the issues of board size and connections were understood to have been achieved.

During the creation process, it was observed that to assemble the entire structure of the Furbot's fuselage, it would be necessary to create different types of fitting parts, in this case for the corners and upper parts. The 25-centimeter-wide and deep structure will consist of two 13-centimeter plates, considering 0.5 centimeters of space for connecting the corners. The 29-centimeter height of the prototype will consist of three layers of interconnected plates, which will total 30 centimeters in height and with this solution, will use a single plate model with connections on all sides.

In view of this objective, three new 3D model models were generated with these requirements, the first being a large plate with connections on all sides and two more connection models, one in the right angle format and the other in the shape of a corner.

Figure 99 - Evidence of the Standard Large Board with Fittings

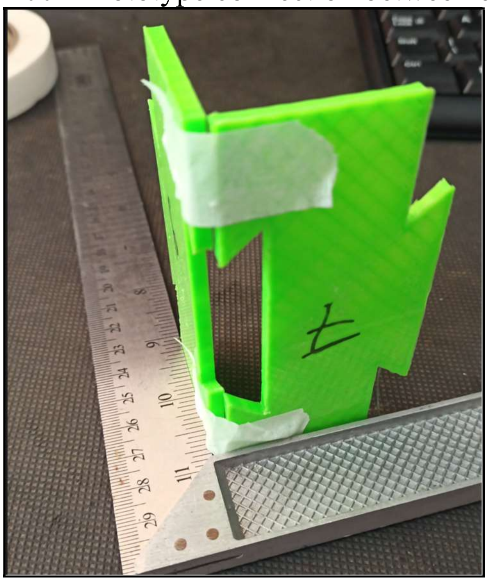


Source: prepared by the author (2024).

Figure Figure 99 illustrates the final version of the standard large plate with the measurements of 13 centimeters wide, 10 centimeters deep and 1 centimeter high. This model was generated with PLA material and took approximately five hours to generate.

The next objective to be achieved is the connection of the connecting corners between parts, as illustrated in Figure 100, a sketch of the demand in relation to the square is observed.

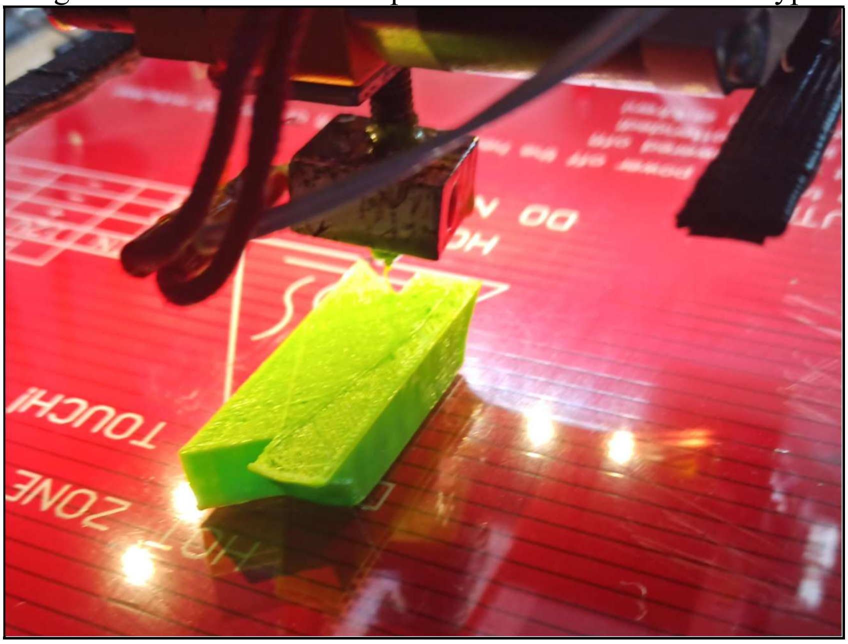
Figure 100 - Prototype connection between corners



Source: prepared by the author (2024).

The two 3D models designed for this purpose were printed, to later carry out the connection test and completion of this step, as shown in Figure 101.

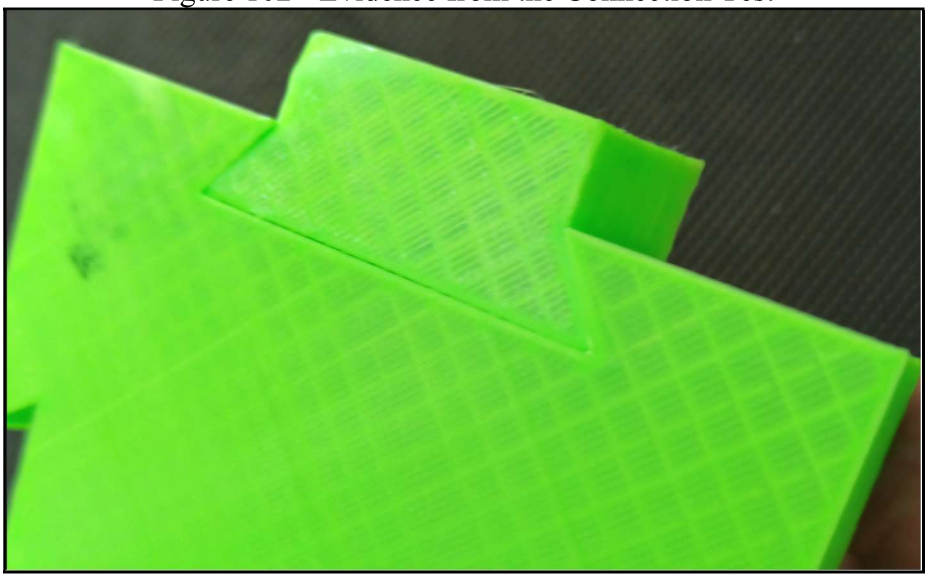
Figure 101 - Evidence of Impression of Connection Prototype



Source: prepared by the author (2024).

The impressions of the two types of connection occurred smoothly and quickly. The duration of the printing took around 30 minutes each piece, as illustrated in Figure 101. After all the prototype parts were finished, the fitting test between parts was performed, which were successful in the first attempt, as shown in Figure 102.

Figure 102 - Evidence from the Connection Test



Source: prepared by the author (2024).

Figure 102 shows the evidence of the test of connection between plates with the connection part between corners, which makes it possible to create the entire structure of the Furbot fuselage with only three models of standardized parts. The total time used during this prototyping study of the part models was approximately 40 hours.

3.4.3 Key Issues and Solutions

In this session, the main lessons learned during the implementation, testing and adjustments that occurred in the construction of the prototype will be addressed.

Problem with pallets: in the design phase of this prototype, in order to reduce the cost, it was decided to use pallets to create the physical structure of the printer. However, at the beginning of the assembly, it was found that pallets in general are created with wood that is irregular in terms of square and that they do not allow a perfect fitting angle that is necessary for the correct functioning of the 3D printer, which demands precision. All wood fittings must be at exactly 90 or 180 degrees. In view of this situation, it was decided to change the material for 15-millimeter MDF, also reused, and the precision cuts were made by a third-party company.

Signal cables from the limit switches: during the tests, induction problems were identified in the limit control cables that caused the motors to lock, especially the X axis. To solve this issue, the sensor cables were conditioned in another position in order to avoid proximity of the power cables.

LCD display problem: During testing, the LCD display stopped working due to the burning out of the voltage regulator on the Arduino board. The display stopped displaying characters legibly and in some cases operated correctly for a few seconds.

As a palliative solution, tests were carried out with a 7805 integrated circuit in order to regulate the voltage of the circuit, but it was not effective in all cases. The solution to this situation was to plug the Arduino board directly into the USB port. The Ramps board (RepRap Contributors, 2024) version 1.4, being an open-source hardware, contains several chronic problems and failures that are likely resolved in later versions. Currently the Ramps board (RepRap Contributors, 2024) is in version 1.6, but at a much higher cost than the version 1.4 board.

X and Y motors operating together: During the firmware configuration, when issuing a command to move motor X, motor Y rotated in the opposite direction. During this stage, tests were carried out with the A4899 stepper motor controllers and DRV8825 in order to identify the problem. Motors were also changed and other attempts were made, until it was discovered that the problem was in the operating configuration of the firmware, which was configured to operate on the COREXY system. This option can be found in the `Configuration.h` file of the *Marlin* firmware, in the `Mechanical Settings section`, where you should comment out the line with the option `defines COREXY`.

Y-axis movement problems: it was found that the Y-axis was having movement problems due to excess weight on the axis. The structure was forcing the motor too much that it had to have its VREF set to 0.75 A. The solution to this situation was to change and align the slide to flow smoothly and without locking. The VREF of the stepper motor controller was again set to a voltage of 0.50 ampere, due to the high VREF causing the motor to heat up.

Z-axis mounting: During the distance and torque calibration of the Z-axis motor, several adjustments were made to the stepper motor controller configuration. The combination of the torque setting can be mentioned, with the reduction from 1/16 step to 1/8 step in order to increase the torque of the engine. This configuration from 1/16 to 1/8 step did not impair the resolution because this shaft uses threaded bar, but it was found that it did not solve the problem in its entirety. Geometry tests were also carried out, replacement of slides with more bearings, tests with oil and blue grease to improve the flow of the slides.

During these adjustments, at the time of VREF adjustment of the stepper motor controller, the Ramps board (RepRap Contributors, 2024) burned, due to the plaintiff touching the tip of the Philips wrench on one of the pins of the stepper motor driver. After replacing the Ramps plate (RepRap Contributors, 2024), the stepper motor controller plate and finalizing the adjustments to the Z-axis motor, the solution to the problem was found and was in the alignment of the motor in relation to the shaft that runs the threaded bar, which required fine adjustment to be at a perfect angle of 180 degrees throughout the shaft's operating stroke.

Assembly of the heated table: During the installation of the heated table, the need arose to fix the temperature sensor in the specific hole for this purpose, in order to carry out the correct temperature measurement. In order to reduce the cost, high-temperature silicone was initially used, used in automotive engine blocks, which according to the manufacturer, withstands temperatures above 240 degrees Celsius. The cure of this product occurs in 24 hours and after waiting the time determined by the manufacturer, it was found that the sensor was not fully fixed on the table. A new application of the product was carried out and after 72 hours new tests were carried out, but without success.

In view of this situation, an alternative was sought for this purpose, where a roll of Kapton tape was purchased, which is a tape developed with polyamide, a material that stands out for its insulating capacity and resistance to temperatures between -269 and 400 degrees Celsius. Fixing with Kapton tape solved the fixing problem.

During the heating test of the table, it became necessary to replace the table's power cables, from 1.5 cables to 2.5 millimeter silicone cables, designed to withstand up to 180 degrees Celsius, according to the manufacturer. This change was necessary due to the heating due to the high demand for current flow.

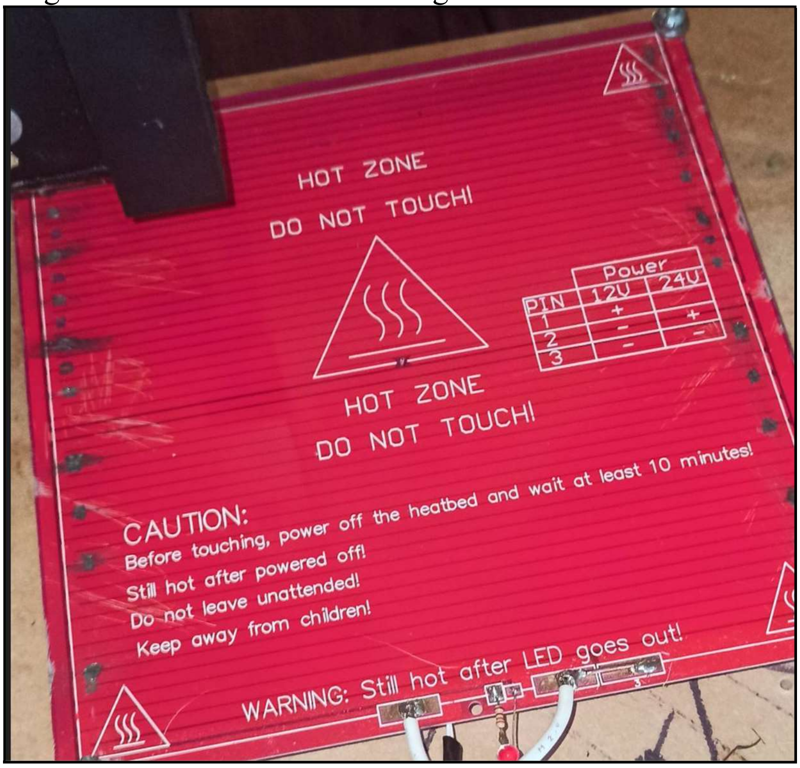
During the heating tests of the hot bed, it was found that the temperature quickly reaches 60 degrees, but the software crashes when it reaches temperatures that vary between 78 and 85 degrees depending on the weather situation carried out during the tests. Due to this issue, the firmware was reconfigured to operate within the board's boundaries and had its maximum operating temperature set to 78 degrees Celsius, which is sufficient for PLA material, but insufficient for ABS material.

Extruder adjustments: during filament tensile tests, where the process consists of sending a 10 millimeter of filament tensile via software and comparing the amount of traction filament with a physical shape ruler. The adjustment process must be repetitive, using a rule of three until the desired calibration is achieved. During this stage, the VREF of the extruder's stepper motor controller was fine-tuned, which was initially set at 0.40 ampere and was changed to 0.75 ampere to find out if the traction problem was a matter of torque in the motor. After tests, it was found that the problem was not torque, but the filament fixation, which during the tests became addicted because the same piece of filament was always being used. By replacing it with a new stretch of filament, the filament traction flow was solved.

Increased heating capacity of the heated table: in order to increase the heating capacity of the table, a test was carried out with the unblocking of tracks on the heated plate in order to reduce the electrical resistance of the plate and increase the circulation of electric current to result in an increase in temperature. The technique used for this purpose resulted in the joining of some trails, shown in Figure 103.

The composition of the heated table plate consists of a structure of long tracks that meet from one end of the plate to the other. The technique used was to shorten the path of these tracks to reduce the electrical resistance that was originally measured at approximately 1 ohm and after this adjustment was measuring 0.75 ohms. The result of this adjustment resulted in an increase in the heating capacity of the plate to up to 92 degrees Celsius, but resulted in several problems, such as problems in the alignment of the glass in relation to the plate, due to welds, in addition to forcing the 12-volt power source too much and causing problems in the stepper motor controller on the X axis, on the voltage regulator of the Arduino board and on the LCD display.

Figure 103 - Evidence of welding on the heated table tracks



Source: prepared by the author (2024).

This test was unsuccessful and the adjustments to the board tracks were removed. After the heated bed features returned to the original format, it took a while to adjust the printer again. Tests were carried out with another 12-volt source, replacement of stepper motor controller that was faulty.

Engine warm-up during testing: During the initial tests with stepper motors, the engines were found to be overheated. The palliative solution was the installation of a heat sink joined with thermal paste in order to dissipate the heat generated by the engine shell. This situation was solved with the repositioning of the slides, lubrication and new regulation of the VREF of the engines. After several tests, the VREF was set to the minimum voltage without impairing torque and speed. The final and stable values for the shaft were approximately 0.40 amperes for the X, Y and extruder axes and 0.30 amperes for the Z axis motor.

Thermal protection via software: during the first printing tests, it was found that the temperature of the heated bed fluctuates easily with the ambient temperature. A simple wind current is enough for the heated table plate to oscillate 2 degrees and the software to freeze due to thermal failure, identified by the message `Thermal runaway protection`. The resolution of this situation was achieved by reconfiguring the firmware in the `configuration_adv.h` file in the `Thermal settings` section with the change of the `THERMAL_PROTECTION_HYSTERESIS` parameter from 2 to 4 degrees in order to increase the temperature oscillation tolerance.

3D printing tests of the first parts: at the beginning of the first prints, there were many problems with the part detaching from the glass, resulting in the deformation of the part in addition to dirtying the entire print head with melted filament. This situation was solved by fine-tuning the print speed on the first layer via software and by aligning and balancing the print bed manually.

GT belts: the original design of the printer conceived operation with threaded bars in the X, Y and Z axes due to the low cost. It was assembled with threaded bars and worked satisfactorily, but it was found that the engines overheated due to the excess movement required to advance on the axles. To move 10 millimeters, approximately 5000 steps were needed in the engine. The issue of axle maintenance was also a factor to be taken into account, as it required manual movement of the axles through the gears if there was a need for any adjustment or maintenance. In some cases, the entire structure had to be dismantled and reassembled. The most important factor found was the performance in the print job, which was very slow, reaching a maximum speed of 3 millimeters per second.

Replacing it with the GT belt kit and pulleys increased the printing speed by up to 10 times because the motors needed to rotate less to achieve the same goal. In a comparison of 10 millimeter feed with threaded bar, 5000 turns were required and with the GT belt it oscillated between 80 and 160 turns according to the micro step configuration of the motor controller. Maintenance has become much simpler because the motors when they are not energized allow the free movement of the shafts. The only negative factor of this solution is the maintenance of belt tensioning, which becomes necessary on average every 20 hours of printing, due to the natural wear and tear of the belt that has rubber in its composition.

PID Auto Tune Configuration: the firmware configuration has as standard the heating system called Bang-Bang which consists of a heating system that turns on the table and extruder resistances until it reaches the temperature stipulated by the sensor and turns it off. This process occurs cyclically in order to maintain the configured temperature. During the tests, this system demonstrated deficiencies because there is a temperature oscillation between the activation of the resistors, resulting in small deformations in the printed part.

To solve this situation, the firmware had its heating system configured to use the PID Auto tune functionality, which will not be covered in detail in this work, but there are several tutorials on the internet on the subject. The process consists of executing a predetermined and configurable number of warm-up attempts and then the firmware returns to the console the optimal values for the PID that must be configured.

After this adjustment, a significant improvement in the quality of the prints was observed, especially during the tests with the ABS material, which corrected various types of deformations resulting from small temperature fluctuations.

Problems with filament shrinkage: during the tests, several problems were found due to the leakage of melted filament by the threads of the nozzle and top of the print head and the creation of nodules was observed during the printing of the part. These problems were minimized with the retraction configuration in the slicing software, but it can be said that there is no formula that fits all cases. Each object shape, extruder temperature, filament quality and print speed can cause this effect and in the cases tested, they were minimized through trial and adjustment. The most acceptable value obtained during the tests was the fixed retraction setting at 4 millimeters.

Problem of jamming and knotting in the filament roller: this situation was observed in long print jobs of more than two hours. It was noticed that in some cases the print was lost due to the formation of knots in the filament roll due to the characteristics of the PLA filament tested. To solve this situation, a filament holder was 3D printed to control the filament flow and avoid this type of situation.

3.4.4 Comparison with related works

Chart 5 presents a comparison between the characteristics of this study and the related studies. The common characteristics between all the works are the use of open source hardware and software and reused parts for development in order to build a low-cost 3D printing solution.

Regarding the objectives, the work most similar to the one proposed is that of Zucca and Machado (2019). Both used the Arduino Mega 2560 and Ramps (RepRap Contributors, 2024) version 1.4 boards with *the Marlin firmware*. The difference is that the work of Zucca and Machado (2019) focuses on the creation of prototypes of the agricultural environment and the proposed work focuses on the issue of detailed assembly of the printer structure, low cost and reuse of components.

The four studies evaluated used open-source firmware. The work of Batista (2021) uses the *Teacup* firmware, while the work of Level *et al.* (2022) used the GRBL firmware and the others used the *Marlin* firmware. The *Teacup* and GRBL firmwares are more limited firmwares, but compatible with the Arduino Uno, which is simpler and has fewer pins compared to the Arduino Mega 2560, however they offer fewer advantages and features.

Chart 5 - Comparison of this study with its correlates

Characteristics	Level *et al.* (2022)	Zucca e Machado (2019)	Batista (2021)	Work developed
Z-axis motors quantities	2	2	2	1
Firmware	GRBL	Marlin	Teacup	Marlin
Board	Arduino Uno	Arduino Mega 2560 and Ramps 1.4	Arduino UNO e CNC Shield	Arduino Mega 2560 and Ramps 1.4
X and Y axis drive	Steel bar and linear guide	Stainless steel bar and linear guide	Steel bar and linear guide	Telescopic slides
Reuse of parts from other devices	No	Yes	Yes	Yes
Physical structure	Mounted	Bought	Mounted	Mounted
Limit Control	No	Yes	No	Yes

Source: prepared by the author (2024).

The work developed in relation to the others, uses only one motor to move the Z axis, but it manages to perform the same tasks compared to the other works compared, enabling a reduction in cost, weight, maintenance and complexity in the prototype. An important issue to comment on is that to operate with two motors there is a demand for both shafts to operate in movement synchrony. Even withS the motors connected to the same output as the Z axis, there are movement timing issues that may require clearances or small differences in rotation, among other factors.

All the works reused components from other devices, such as the removal of stepper motors from old printers, however the work of Level *et al.* (2022) was unable to use them and had to purchase new engines to proceed with the prototype. An important issue in the reuse of components from other devices is the lack of documentation due to the fact that they are usually the intellectual property of the manufacturer, who has no interest in disclosing technological information about its products due to competitive market issues.

With the exception of the work developed, which used telescopic drawer slides to move the X, Y and Z axes, all the other works used linear bars and guides in their projects. The slide is a cheaper material and is not intended to be used in solutions that require precision, but the proposed work managed to achieve its objectives even with a lower cost component. Linear guides are bars, usually made of steel and have specific bearings for use in situations that demand precision, usually used in all types of machines have this demand, but the cost is much higher compared to simpler solutions.

In terms of the physical structure of the works developed, only the work Zucca and Machado (2019) purchased the prefabricated wooden structure and carried out only the assembly. All the other works cut the wood in different shapes and variations and carried out the assembly in a more artisanal way.

The work of Level *et al.* (2022) and Batista (2021) use simpler firmwares that did not offer the end-of-stroke control functionality, while the other works have this functionality implemented. Limit switches are useful for all axes to automatically return to their origin at the start of each print.

Batista (2021) emphasizes that one of the biggest problems faced while carrying out the work was the excess clearance between the plastic bushings and the linear guides, which made it very difficult to achieve the necessary precision. Initially, the idea was to use only one linear bar for each axis, but it was realized that this was not possible, as any sinuosity of the bar, no matter how small, would cause an inadmissible loss in the precision of the movement (Batista, 2021). As a solution, Batista (2021) used two parallel linear guides per axis to solve the problem.

4 CONCLUSIONS

This work presented the construction of a low-cost 3D printer. For this purpose, the assembly of the structural, mechanical and electronic parts was carried out. Recyclable parts, Arduino Mega 2560 board, Ramps version 1.4 electronic kit, other peripherals and a set of firmware and software with the necessary functionalities to make the project feasible were used.

The necessary tools and equipment used met the needs of the project, making the 3D printer functional and capable of performing all the proposed functionalities with excellent quality. The hardware and software used, from the development environment to homologation, demonstrated that it is possible for the development of a 3D printer to work perfectly with low-cost components and use only open source software. The use of the Arduino Mega board in conjunction with the Ramps version 1.4 board, in addition to its low cost, will allow the project to be modularized and customized for future improvements. It can be understood as a great advantage over commercial printers in the same segment, which in this matter are very limited due to proprietary technology. The ATMega2560 microcontroller used in the Arduino board demonstrated excellent orchestration capability of various peripherals and realized perfect synchronization after extensive configuration and adjustments. This synchronism involved four stepper motors, three limit switches, two temperature sensors, two resistors, as well as real-time updating of the LCD graphic display and 3D printing software, among other features.

The construction of a 3D printer involves several areas of knowledge, including knowledge of woodworking, robotics, mechanical and electrical engineering, prototyping and modeling of objects in three dimensions, and electronics. To achieve the expected results, a lot of discipline is needed. patience and dedication, due to the need to assemble and disassemble components in the adjustment and alignment phases of printing.

The assembly and adjustments of the mechanical part was the most challenging during the entire project. The wooden frame was assembled and disassembled three times until it reached an acceptable level of print quality. During the project, there were several adjustments in the issue of axle movement, such as locks, clearances in rushes and heating problems that required adjustments for their complete resolution.

This work is also intended to show that the operation of a 3D printer is very different from a traditional 2D printer. Traditional commercial 2D printers are currently at a high level of abstraction to perform printing. To perform the operation, just select the printer and press the print button and the printing is carried out and finished in a simple way. In comparison, a 3D printer requires several fine-tunings, before, during and after printing. It can also be said that each 3D model to be printed demands a specific configuration for that object, according to its shape, rigidity, filament used, ambient temperature, among other variables. There is no standard setting that is compatible with all print models.

This work was relevant because it showed the possibility of building a 3D printer with low-cost components, hardware and open-source software. It is also expected that it will contribute and encourage students and enthusiasts to use this technology to apply in more specific studies, such as rapid prototyping for other areas, including architecture, medicine, engineering and electronics. The tests carried out with the prototype showed excellent results and it can be concluded that all the proposed objectives were achieved, exceeding the expectations of the beginning of the project.

The main advantages observed in the work are:

a) low cost;

b) excellent cost-benefit;

c) Easy maintenance;

d) low coupling by using open source hardware and software;

e) ease of customization by not using proprietary hardware;

f) uses only one motor on the Z axis, which reduces cost, weight and complexity of the project.

Among the main limitations of the work is the issue that due to the prototype being open and low cost, it is not able to operate correctly with ABS material, as it would be necessary to readjust the entire set to achieve this goal. One can also mention the issue of the aesthetic part due to the cables and gears being visible and finally the prototype could be lighter and more compact.

The question of the prototype being open, it is understood that it was not designed to have thermal insulation, necessary for the correct functioning and operation with the ABS material. To make this possible, the entire printing area must be surrounded by an isolated and temperature-controlled environment in order to avoid deformation of the material. The heated bed will also have to be more powerful, due to the high temperatures that are required to maintain the adhesion of the material to the printing base. The structure of gears and cables must be able to operate in an environment with temperatures equal to the temperature of the heated table and must be isolated from the external environment. Electronic boards, motors and other components must be isolated from the internal printing environment to avoid overheating. The entire electrical scheme must be redone and be compatible with this demand for power and thermal tolerance.

It is believed that 3D printing has a lot to evolve and it is observed that currently the most modern 3D printers in the segment print with up to four colors of filament. This thought refers to the phase of the arrival of dot matrix printers in the 90s in the country, where they printed with ribbons of only one color and with the evolution new technologies accessible to the public emerged, such as the dot matrix printer with two-color ribbon, then four colors. Following this, inkjet printer appeared and after laser printing. It is also believed in the evolution of scanners that capture images and objects in 3D format that can also contribute to this ecosystem.

4.1 EXTENSIONS

To improve the features of this work or add new ones, the following extensions are suggested:

a) develop a version of a closed 3D printer with a temperature-controlled heating cell system to operate correctly with ABS material;

b) carrying out a study of this technology for civil construction: with a project to create a mortar extruder and later a large-scale 3D printer with the objective of generating a house with this technology;

c) conducting a study to explore this low-cost 3D printer solution, for the creation of 3D prostheses to assist health and community areas;

d) conducting a study of this technology to disseminate teaching about 3D printing for purposes other than rapid prototyping of parts for projects or social programs;

e) creation of a structure to generate 3D printing filament with the recycling of PET bottles and make necessary adjustments to the printer to use this type of filament that is ecologically friendly;

f) to develop a prototype of a heated table based on low-cost resistances with the objective of reaching 120 degrees in a stable way for the use and improvement of this prototype.

REFERENCES

ALLEGRO. **DMOS microstepping driver with translator and overcurrent protection**. [2014?] Disponível em: https://www.pololu.com/file/0J450/a4988_DMOS_microstepping_driver_with_translator.pdf. Acesso em: 12 abr. 2024.

ARDUINO. **Arduino IDE 1.8.19**, 2021 Available at: https://www.arduino.cc/en/software. Accessed on: May 15, 2024.

ARDUINO. **Arduino® MEGA 2560 Rev3**, 2024. Available at: https://docs.arduino.cc/resources/datasheets/A000067-datasheet.pdf. Accessed on: May 15, 2024.

BATISTA, Ivanildo. **Construction of a low-cost 3d printer with alternative materials**. 2021. Course Completion Paper (Graduation in Electrical Engineering) – Uninter International University Center, Cascavel, 2021. Available at: https://repositorio.uninter.com/handle/1/1273?show=full. Accessed on: 5 set. 2023.

CELERINO, Gleydson Galvão *et al.* **Building a low-cost 3d printer using open-source hardware and software**. 2022. 46 f. Final Paper (Graduation in Technology in Systems Analysis and Development) – Federal Institute of Science and Technology of Pernambuco, Recife, 2022. Available at: https://repositorio.ifpe.edu.br/xmlui/handle/123456789/867. Accessed on: 5 set. 2023.

EVANS, Brian. **Practical 3D Printers:** The Science and Art of 3D Printing. New York: Apress, 2012.

FREECAD TEAM. [**FreeCAD].** 2024. Available at: https://www.freecad.org/. Accessed on: May 15, 2024.

FURB. **FURBOT.** Blumenau, 2024. Available at: https://furbotldtt.wixsite.com/my-site-1. Accessed on: May 16, 2024.

HORNE, Richard; HAUSMAN, Kalani Kirk. **3D Printing for Dummies**. 2. ed. New Jersey: John Wiley & Sons, Inc; Hoboken, 2017.

LEVEL, Jaimakson Rafael de Melo *et al*. The DIY Philosophy: reusing electronic scrap for the construction of a low-cost 3D printer. **Revista Novafisio,** [*s. l.*], v. 26, n. 109, 28 Apr., 2022. Available at: http://dx.doi.org/10.5281/ZENODO.6502998. Accessed on: 13 set. 2023.

MARLIN. [**Marlin Firmware 1.1.9**]. 2020. Available at: https://github.com/MarlinFirmware/Configurations/tree/release-1.1.9. Accessed on: May 15, 2024.

MOTION KING. **17HS Stepper Motor - 42mm (1.8 degree)**. [2006-2024] Disponível em: https://www.motionking.com/products/Hybrid_Stepper_Motors/17HS_Stepper_Motor_42mm_1.8degree.htm. Acesso em: 15 maio 2024.

MURTA, José Gustavo Abreu. **All About A4988 DRIVER and Stepper Motor**. 2022. Available at: https://blog.eletrogate.com/driver-a4988-motor-de-passo-usando-o-arduino/. Accessed on: 11 Apr. 2024.

POLYLACTIC ACID. *In*: WIKIPEDIA, the free encyclopedia. Florida: Wikimedia Foundation, 2024. Available at: https://pt.wikipedia.org/w/index.php?title=Poli%C3%A1cido_l%C3%A1ctico&oldid=67795277. Accessed on: May 15, 2024.

PRUSA, Josef; STRITESKY, Ondrej; BACH, Martin. **Basics of 3D Printing with Josef Prusa**. Praga: Prusa Research, 2020.

QUEIROZ, Leonardo de Jesus *et al.* **Construction of a 3D printer:** Low-cost open projects and possibilities of application in education. 2019. Final Paper (Graduation in Electrical Engineering) – State University of Western Paraná, Itaipu Technological Park Foundation, Foz do Iguaçu, 2019. Available at: https://repositorio.uninter.com/handle/1/1273. Accessed on: 5 set. 2023.

REPEAT. [**repeat-host**]. 2024. Available at: https://www.repetier.com. Accessed on: 12 Apr. 2024.

REPRAP CONTRIBUTORS. **RAMPS 1.4 Assembly Guide**. 2024. Disponível em: https://www.reprap.org/mediawiki/images/0/06/RAMPS_dossier.pdf. Acesso em: 15 maio 2024.

RISCO-CASTILLO, Miguel. **3D BLTouch**. 2023. Available at: https://github.com/mriscoc/Ender3V2S1/wiki/3D-BLTouch. Accessed on: 11 Apr. 2024.

SILVA, Cesar Ricardo Câmara da. **Curriculum of the Lattes curriculum system**. [Brasília], 29 Sept. 2017. Available at: Available at: http://lattes.cnpq.br/3767853300683676. Accessed on: May 15, 2024.

SILVA, Gabriel Beires; SILVA, Luis Henrique Pereira da. **Prototyping of a low-cost 3d printer**. 2023. Course Completion Work (Graduation in Mechanical Engineering) – Faculdade Evangélica de Goianésia, Faceg, Goianésia, 2023.

THINGIVERSE. [**Library of Relief Forms**]. 2024. Available at: https://www.thingiverse.com. Accessed on: May 15, 2024.

TRIMBLE INC. [**3DWareHouse**]. 2024. Available at: https://3dwarehouse.sketchup.com/. Accessed on: May 15, 2024.

TRIMBLE INC. [**SketchUP].** 2023. Available at: https://www.sketchup.com/pt-br. Accessed on: May 15, 2024.

WISINTAINER, Miguel Alexandre. **Curriculum of the Lattes curriculum system**. [Brasília], 18 jul. 2014. Available at: http://lattes.cnpq.br/0989671167867867. Accessed on: May 15, 2024.

ZALM, Erik Van Der *et al.* **Marlin Firmware**. 2023. Disponível em: https://marlinfw.org/. Acesso em: 9 set. 2023.

ZUCCA, Rafael; MACHADO, Carlos Alberto Chuba. **Development of a low-cost 3D printer for prototyping parts for rural areas.** 2019. Dissertation (Master's Degree in Agricultural Engineering) – Federal University of Grande Dourados, Dourados, 2019. Available at: http://repositorio.ufgd.edu.br/jspui/handle/prefix/943. Accessed on: 5 set. 2023.