Design report

Tau 3D Printer

A small and low-cost 3D printer

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1 Introduction

This document reports the development of a small and low-cost 3D printer called Tau, shown in Figure 1. The printer is named after the Tau particle, a very small elementary particle from the family of the Leptons.

Here, all steps in the development of this equipment will be described, as well as the reasons for making each decision. There are countless 3D printers available on the market, with different dimensions, features and costs. However, designing a functional and effective equipment guarantees a lot of learning, which is the main objective of this project.

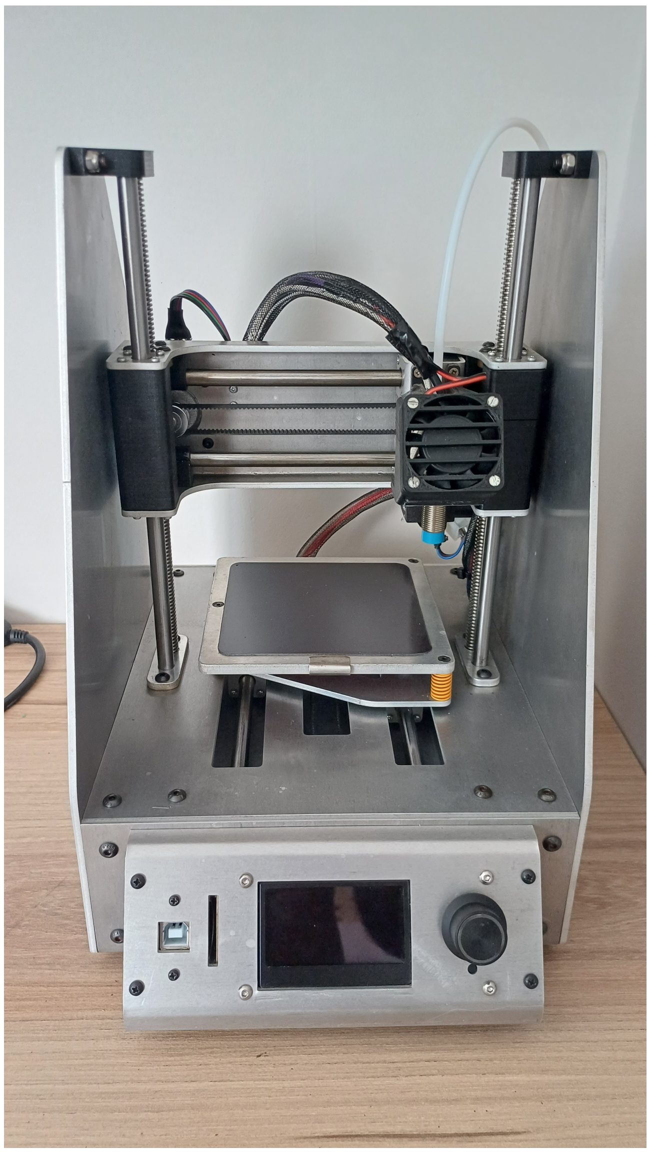


Figure 1: Tau 3D printer

2 Technical requirements

The main technical requirements established for this project are:

- Maximum dimensions of 300 x 300 x 350 mm (L x W x H);
- Maximum cost of R$1500.00 (approximately $300.00);
- Ability to print with ABS, PLA and PETG;
- Ability to print from SD card or USB port;
- Ability to perform sensorless homing;
- Have a removable and flexible printing surface.

As it is a low-cost printer, no specific requirements have been established for parameters such as printing speed, quality and precision, although all decisions seek to optimize these parameters.

3 Printer design

There are currently many 3D printing technologies. The most popular ones are: FDM (Fused deposition modeling), SLA (Stereolithography) and SLS (Selective laser sintering). More information about these technologies at: formlabs.com.

The vast majority of 3D printers used outside of industry are of the FDM type, as other technologies bring higher construction and printing material costs. This factor also makes these technologies unfeasible for this project. Despite having disadvantages in relation to the quality and precision of printed parts, FDM technology is sufficient for the development of functional prototypes.

After selecting the technology, it is necessary to choose the type of FDM printer. There are several combinations and each source has different classifications. A good summary of the main types can be found at: 3dsourced.com.

Due to the simplicity of design, configuration and maintenance, the Cartesian type was selected. Despite its simplicity, there are many high-quality printers on the market with this configuration. Next, the development of the project's various subsystems will be analyzed.

3.1 Movement transmission

The movement transmission subsystem can consume most of a 3D printer project budget, depending on the components used. However, by taking the necessary care, it is possible to obtain good results with low-cost components.

One of the decisions to be made is regarding the use of linear rods or linear rails. Linear rails have numerous advantages: they support greater load, guarantee greater precision and occupy a smaller volume. However, they have the disadvantage of high cost. A most complete comparison between linear rods and linear rails can be found at: birailmotors.com.

In order to keep the cost low, sets of linear rods and linear bearings with a nominal diameter of 8 mm were applied to all axes. Some of these linear rods are shown in Figure 2. Although thinner linear rods are sufficient for the printer in question, the 8 mm diameter is commonly applied in many benchtop machines, which makes their cost lower than that of thinner rods. The linear bearings were mounted inside plastic parts manufactured by 3D printing and then attached to each of the carriages, like shown in Figure 3.

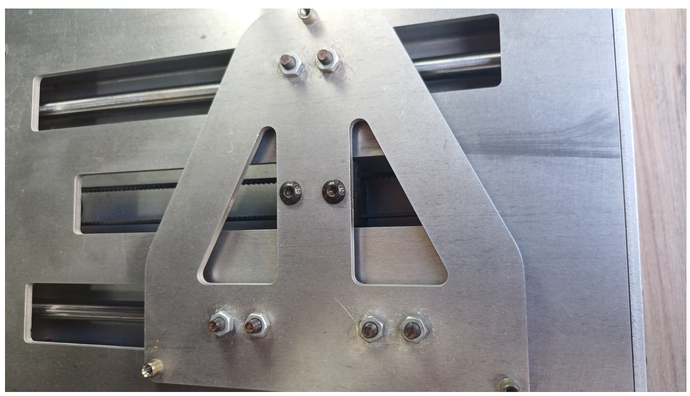


Figure 2: Linear rods

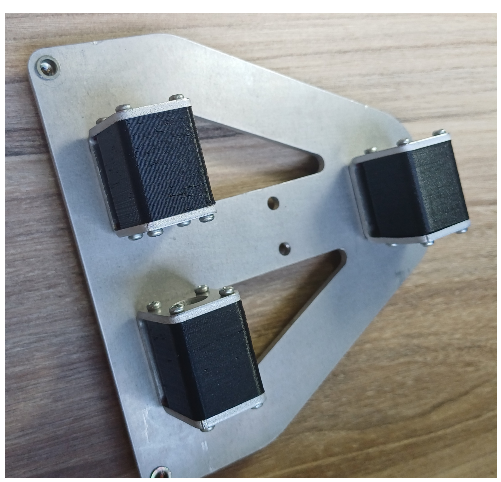
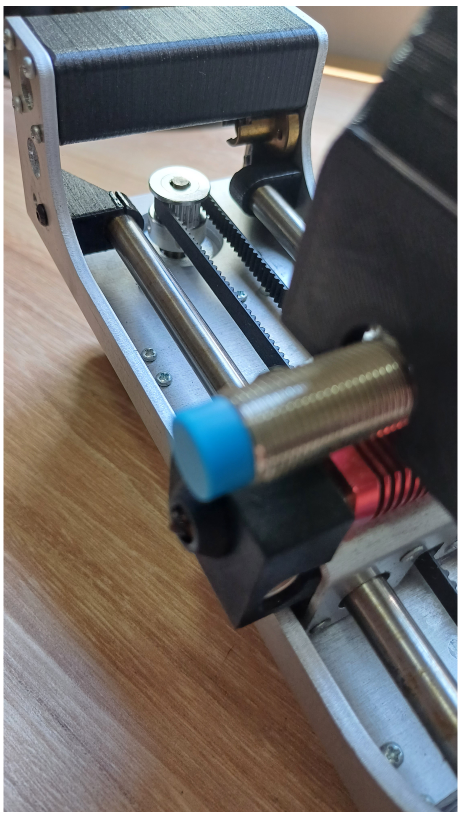


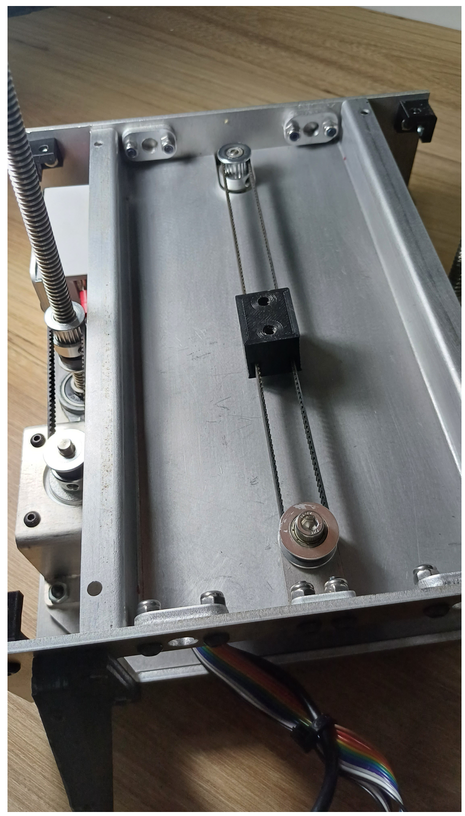
Figure 3: Linear bearings

Another important decision is regarding the use of belts or leadscrews to transmit the movements of the stepper motors to the carriages. Belts allow for greater speed of movement, but support less load. Leadscrews, on the other hand, support greater loads but allow slower movements. A most complete comparison between belts and leadscrews can be found here: blog.parker.com.

The most common choice in most 3D printers is the use of belts on the X and Y axes, and the use of leadscrews on the Z axis. This was also the choice made for Tau. On the X and Y axes, 6 mm wide GT2 belts were used, cut to the appropriate length for the dimensions of the respective carriage. These belts are shown in Figure 4.



(a) X axis belt



(b) Y aixs belt

Figure 4: X and Y belts

In the Z axis, two leadscrews operating in parallel were applied, with the aim of guaranteeing the alignment of the carriage. These leadscrews are show in Figure 5. To move them, GT2 belts were used to transmit the movement of the stepper motor to the two spindles in parallel, like shown in Figure 6.

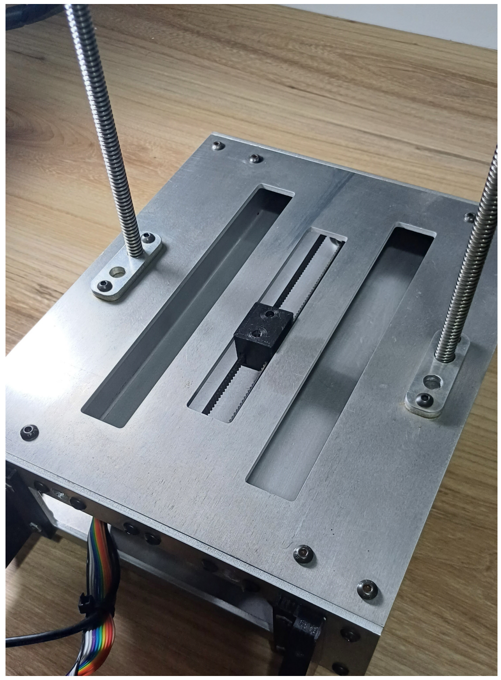
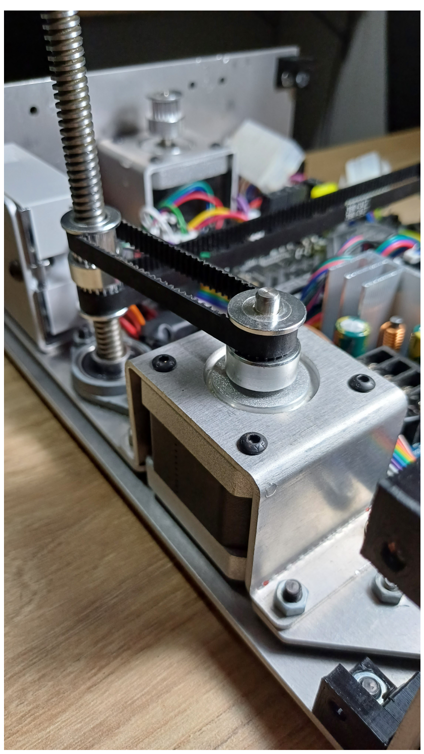
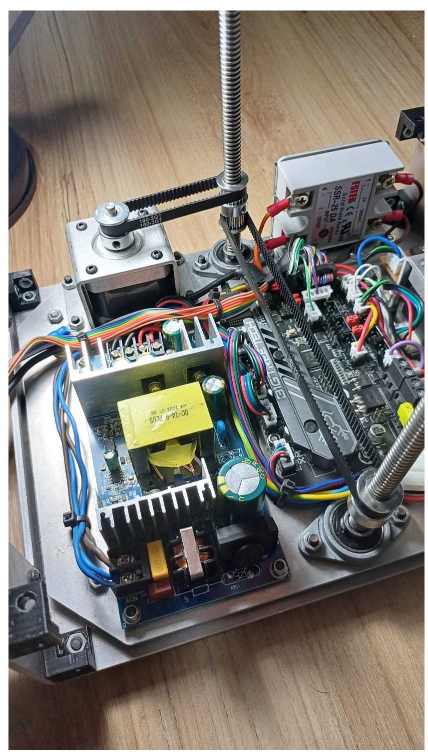


Figure 5: Z leadscrews



(a) Z axis belts - 1



(b) Z axis belts - 2

Figure 6: Z belts

Aiming at low cost, the leadscrews used are of the trapezoidal type, which can be obtained for relatively low prices. A much more reliable option would be to use ball screws, but these have very high costs, incompatible with a low-cost printer. Nuts with trapezoidal thread transform the rotary movement of the leadscrews into linear movement in the Z axis. One of these nuts is shown in Figure 7.

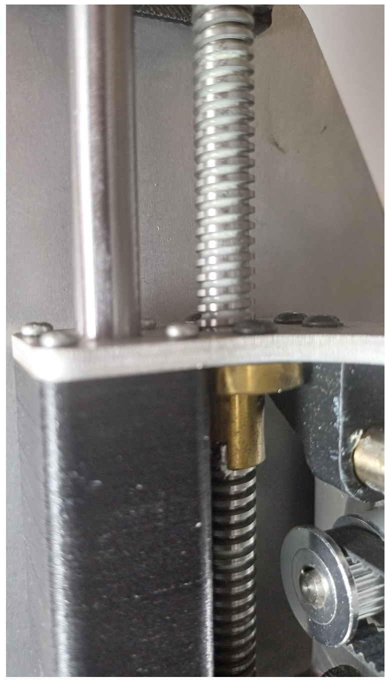
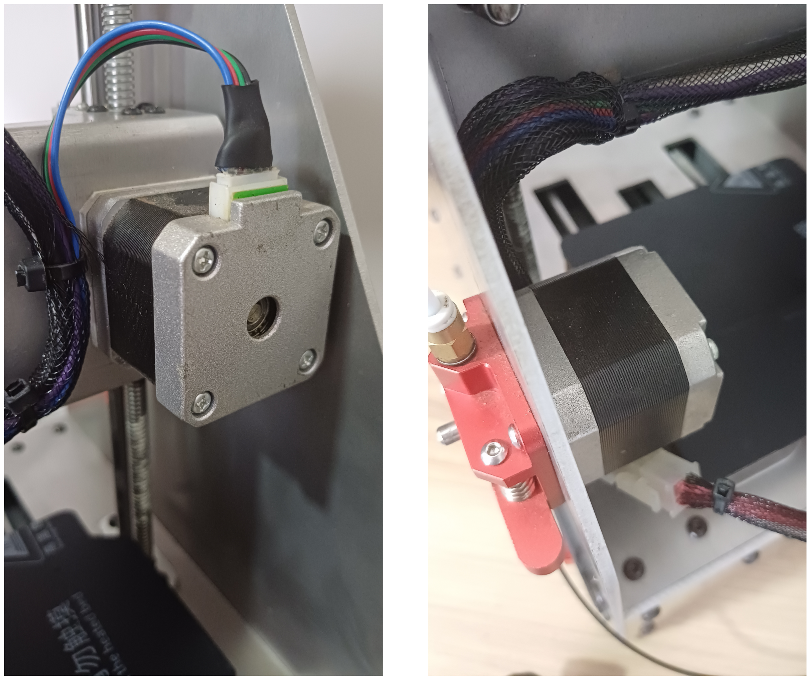


Figure 7: Trapezoidal nuts

3.2 Motors

The stepper motor used in all axes of the printer is the 42BYGHW609. This motor has a resolution of 1.8° and a holding torque of 40 N.cm. The steppers used in the X axis and the extruder are shown in Figure 8. Although the maximum torque provided by this motor is higher than that required on any axis of the printer, the 42BYGHW609 is quite popular, which means that its cost is lower than that of smaller motors, which are less in demand. Furthermore, using the same stepper on all axes allowed the purchase of a kit containing 4 units, which also reduces total costs.



(a) X stepper (b) Extruder stepper

Figure 8: Steppers

3.3 Extruder

The extruder was developed using the Bowden model. In this model, the extruder is mounted on the printer housing and ”pushes” the filament towards the print head, unlike the direct-drive model, in which the extruder is mounted on the print head itself and ”pulls” the filament. A comparison between direct-drive and Bowden extruders can be found at: all3dp.com.

The Bowden model was selected to reduce the dimensions and weight of the print head, allowing faster and smoother movements, as well as better use of the printing area. The extruder is shown in Figure 9. A considerable disadvantage of the Bowden model is the greater difficulty in working with highly flexible or abrasive materials, due to the Bowden tube. However, the main application of this project’s printer is printing with basic materials such as ABS, PLA and PETG.

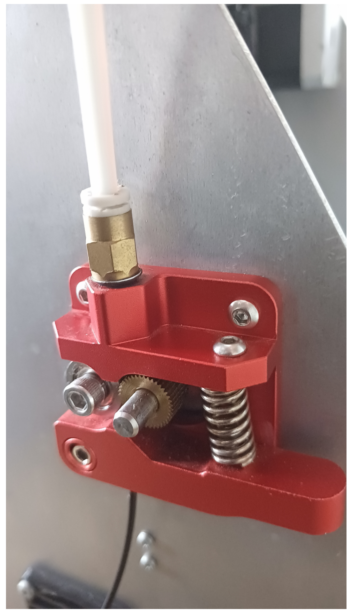


Figure 9: Bowden extruder

3.4 Power

To power the printer, a power cord must be connected to the socket installed on its side, shown in Figure 10. This socket also has a fuse that protects the entire circuit against overloads. From the inside, the terminals of this socket are connected to the input of the power supply. The power supply used has a 24 V output, being capable of supplying up to 9 A. The power supply is shown in Figure 11. This power supply is responsible for powering most of the printer's components.

Figure 10: Power input socket

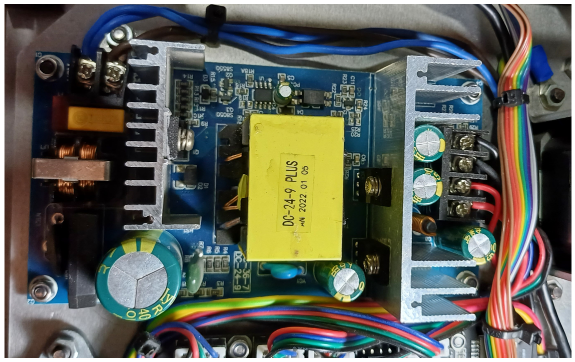


Figure 11: Power supply

3.5 Controller board

The controller board chosen was an SKR Mini E3 V3, from BIGTREETECH, shown in Figure 12. At the time of the project, this was the latest version of the SKR Mini E3 family. Despite the low cost, this board features a 32-bit processor and several other interesting features. It has integrated TMC2209 drivers, which guarantee silent control of the stepper motors, in addition to having the capability of sensorless homing and micro-stepping up to 1/64.

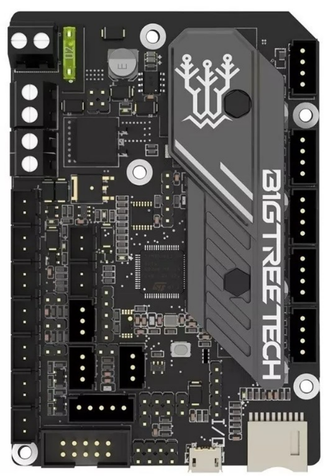


Figure 12: SKR Mini E3 V3

The SKR Mini E3 V3 has interface connectors for 5 stepper motors (XM, YM, ZAM, ZBM and EM), heated bed, heating block, LCD display, 3 fans, 2 thermistors, Z-probe, Neopixel LED and 3 limit switches. It also has features such as filament detection, automatic shutdown and resume printing after shutdown. It has a micro-USB port for communicating with the computer and an integrated SD card reader.

In this project, some of the SKR Mini E3 V3 interfaces were not used and several of them were remapped to meet other needs. The Figure 13 shows the controller board integrated into the system. More information about the SKR Mini E3 V3 can be found at: biqu.com.

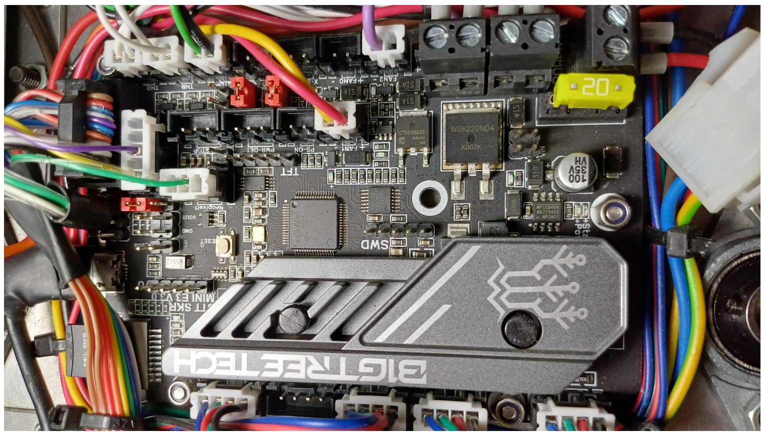


Figure 13: Controller board

3.6 Heated bed

The heated bed, shown in Figure 14 is made from a 5 mm thick aluminum sheet, which ensures that it is rigid and does not suffer deformation. This bed is assembled and coupled to the Y carriage using a set of screws and springs that allow it to be leveled. The springs can be seen in Figure 15.

Figure 14: Heated bed plate

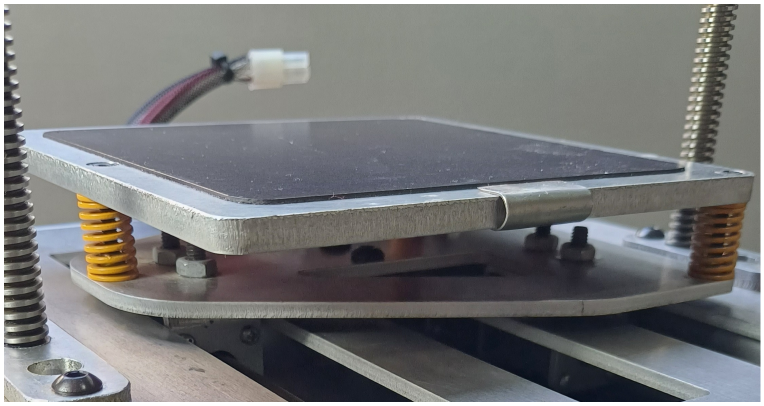


Figure 15: Heated bed springs

The bed was designed with only 3 leveling points, enough for an efficient leveling routine. Many projects use 4 leveling points, but this strategy makes leveling difficult and causes warping in several parts. More information about both options can be found at: drmrehorst.blogspot.com.

Under the bed, a silicone heater was glued with high-temperature silicone adhesive, shown in Figure 16. A 220 V heater was used, allowing rapid heating of the bed without consuming power from the power supply. The heater power goes through a solid state relay. Instead of applying voltage directly to the heater, the controller board controls the solid state relay, shown in Figure 17.

Figure 16: Silicone heater

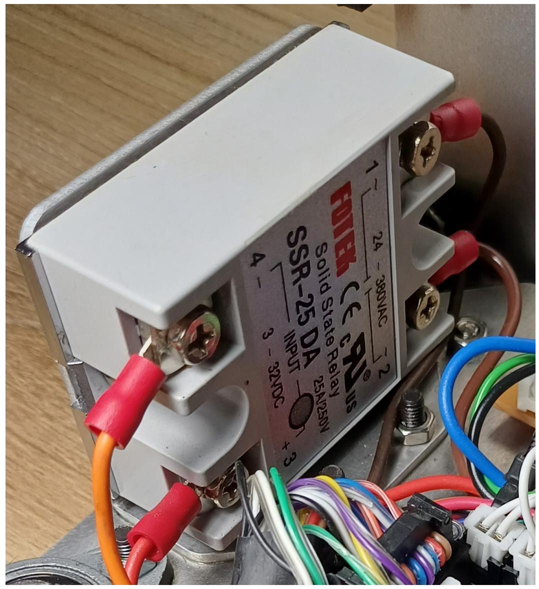


Figure 17: Heater control relay

Between the bed and the heater, an NTC thermistor was installed. A blind hole was made in the center of the bed, where the thermistor was placed with thermal paste.

On top of the heated bed, a removable flexible printing surface was installed. This surface has a magnetic blanket, which was glued to the heated bed. The print surface is then magnetically attached to this blanket and can be easily removed from the bed at the end of each print. The flexibility of the printing surface makes the process of removing the printed part very easy, like shown in Figure 18.

Figure 18: Printing surface

3.7 Probe

An LJ12A3-4-Z-BX sensor, shown in Figure 19, was used as a probe. This is an NPN inductive sensor. Several types of sensors could have been selected, each with its advantages and disadvantages.

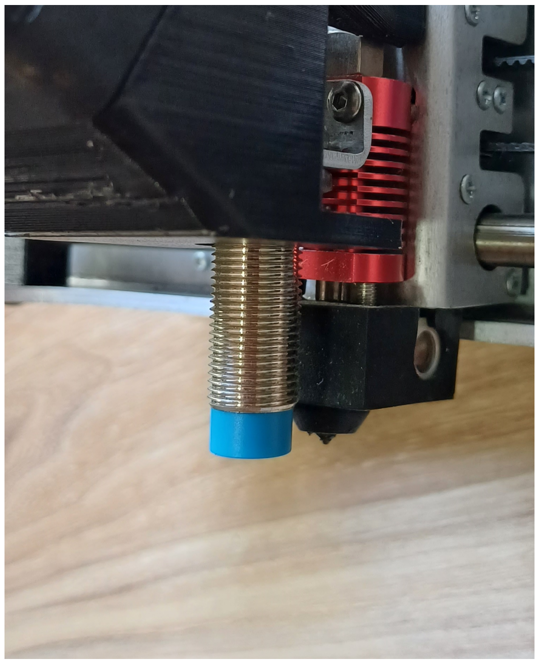


Figure 19: Probe

A capacitive sensor is capable of detecting basically any type of surface, but it is very sensitive to variations in temperature and humidity. An optical sensor can suffer interference from external light, in addition to having difficulty detecting surfaces that reflect little light, as is the case with the printing surface used in this project.

Mechanical sensors, like the BL Touch, are expensive. There are also other types of less popular sensors, such as piezoelectric and ultrasonic. A comparison between the most common types of probe can be found at: 3dsolved.com.

Inductive sensors have a relatively low cost, are not extremely sensitive to environmental conditions (lighting, temperature, humidity...) and do not require contact with the printing surface.

The only problem encountered when integrating an inductive sensor is that it is only capable of detecting ferromagnetic surfaces. The aluminum bed can be detected by an inductive sensor, but the detection distance is quite low. Using the flexible printing surface on top of the bed prevents the sensor from detecting the bed.

To solve this problem, a small sheet of ferromagnetic material was mounted on one end of the aluminum bed, like shown in Figure 20. The firmware has been adjusted so that the Z axis always homes to this plate.

Figure 20: Probe sheet

The supply voltage range of the LJ12A3-4-Z-BX sensor is 6 V to 36 V, and its output voltage is equal to the value used to power it. In this project, the sensor was powered with 24 V, coming from the main power supply. Therefore, it was necessary to add a circuit with an optocoupler at its output, which converts the signal to 5 V, making it compatible with the input on the controller board. This circuit is shown in Figure 21.

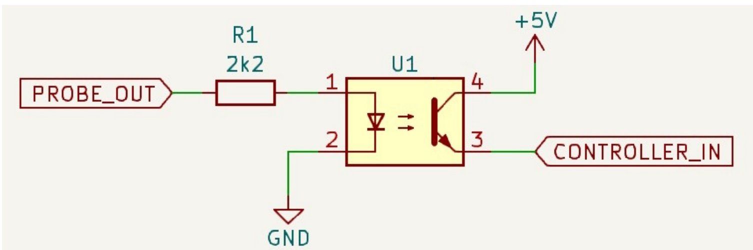


Figure 21: Optocoupler circuit

3.8 Cooling

The printer design has 2 fans. The first of these removes hot air from inside the printer, cooling components such as the controller board and power supply. This fan is shown in Figure 22.

Figure 22: Electronics fan

The second fan, shown in Figure 23, was installed on the printhead to ensure that the cold part of the print head remains cool. This fan was included in the project after the first tests, because, without it, the temperature of the cold part of the printhead would rise and cause the filament to melt before it reached the nozzle. A plastic part directs air from this fan to the printhead body.

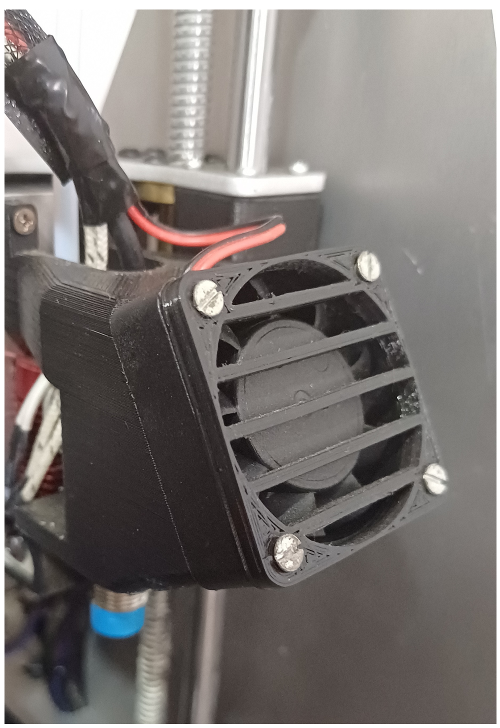


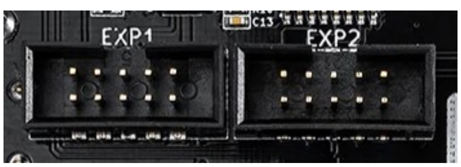
Figure 23: Print head fan

3.9 Display

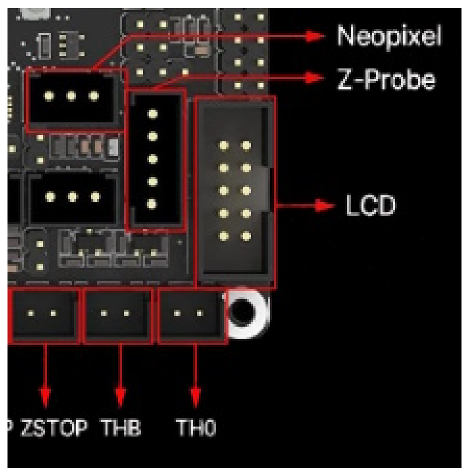
The display selected for this project was the MKS Mini 12864 V3, this being the last version available at the time of the project. This display has RGB backlight, an SD card reader, and is supported by both Marlin and Klipper. More information about this display can be found at: github.com/makerbase-mks/MKS-MINI12864-V3.

This display is directly compatible with several controller boards, but not with the SKR Mini E3 V3. At the time of the project, there were some reports on the internet of people who managed to do this integration partially, without the SD card reader working, for example.

Therefore, display integration was one of the biggest challenges of this project. The MKS Mini 12864 V3 display has two connectors, EXP1 and EXP2, while the SKR Mini E3 controller board has only one connector intended for connecting the display, EXP1. Figure 24 shows these connectors.



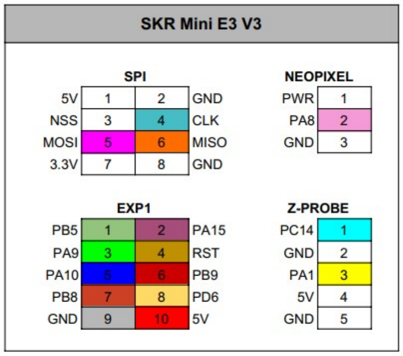
(a) LCD connectors

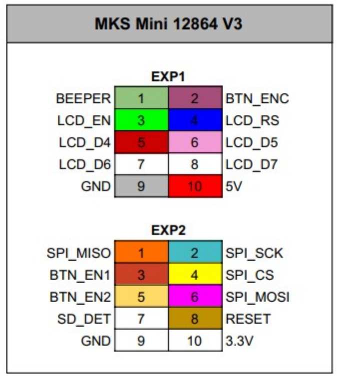


(b) Controller board connector

Figure 24: LCD and controller board connectors

Firstly, therefore, it was necessary to define which pins of the display connectors were important and select pins on the controller board to connect them. These connections are shown in Figure 25. The EXP1 connector does not have all the necessary pins, and therefore, it was necessary to use pins that have other functions as standard and reconfigure them.





MKS Mini 12864 V3		SKR Mini E3 V3
BEEPER	-	PB5
BTN_ENC	-	PA15
LCD_EN	-	PA9
LCD_RS	-	PA10
LCD_D4	-	PB9
LCD_D5	-	PA8
GND	-	GND
5V	-	5V
SPI_MISO	-	MISO
SPI_SCK	-	CLK
BTN_EN1	-	PB8
SPI_CS	-	PA1
BTN_EN2	-	PD6
SPI_MOSI	-	MOSI
SD_DET	-	PC14
RESET	-	RST

Figure 25: LCD pins

It was then necessary to develop a cable capable of making all these connections. This cable is shown in Figure 26. Finally, it was necessary to remap the functions of these pins in the firmware. The integration was a success and all display functions work perfectly, including the SD card reader, like shown in Figure 27.

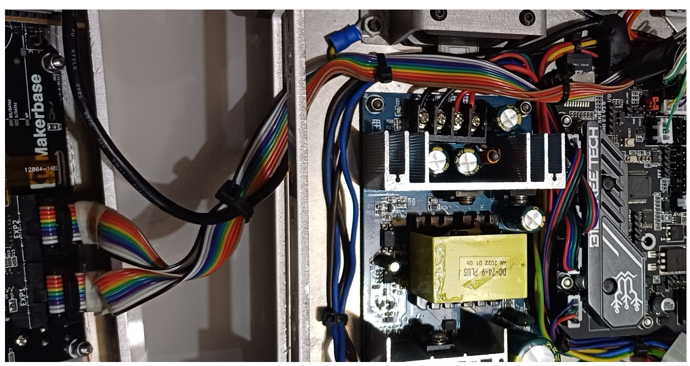


Figure 26: LCD cable

Figure 27: LCD screen

3.10 Firmware

There are several opensource firmware options available for use. Many of them, however, are developed for specific printers or controller boards. Among the multiplatform opensource firmwares, the two most widespread are Marlin and Klipper.

The Klipper firmware, however, uses an external computer to perform the necessary calculations, which would increase project costs. Therefore, Marlin was the firmware chosen for this project.

Marlin is an opensource firmware developed and maintained by the maker community, undergoing constant updates and improvements. It is a highly customizable firmware and allows easy configuration of various features. Marlin is so popular that many companies use it as the basis for their printer firmware. More information about Marlin can be found at: marlinfw.org/.

It was necessary to adjust several features in the firmware, mainly related to the LCD display, SD card reading, stepper motor control and the inductive probe. The Marlin firmware adapted for this project can be found at: github.com/AlanCarvalhoEE/tau-3d-printer.

3.11 Manufacturing and assembly

The printer's frame is made almost entirely of aluminum and plastic. To build the frame, aluminum sheets were cut using a laser cutting machine and some of them were also bent using a press brake. Figure 28 shows one of these parts. These processes have limitations in terms of part complexity, but they are inexpensive and, if used wisely, offer many possibilities. Aluminum, in addition to being a relatively cheap material, provides low weight and resistance to corrosion.

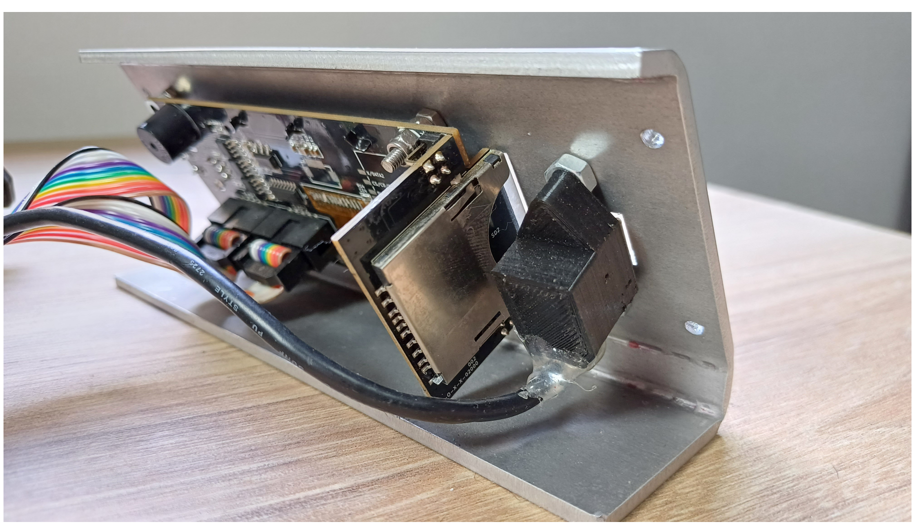


Figure 28: LCD assembly aluminum sheet

The plastic parts were manufactured using a 3D printer. Most of them were made of ABS, but there are also PLA and PETG parts. These are the most complex parts, difficult to manufacture with aluminum. They were used to assemble the structure parts, the linear bearings and the linear rods, for example. Figure 29 shows one of these parts.

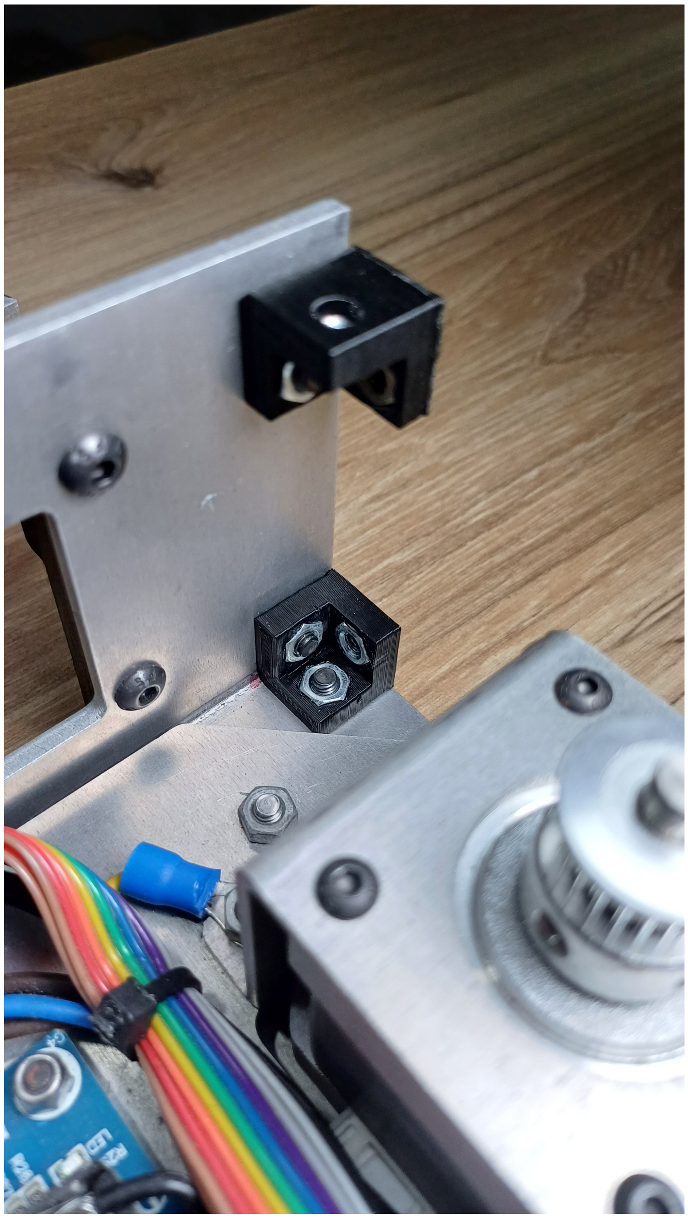


Figure 29: Frame assembly plastic part

Most of the electronic components were assembled into a single sheet of aluminum and then mounted inside the printer base, like shown in Figure 30. In the bottom of the printer, rubber feet were assembled to smooth vibrations, like shown in Figure 31.

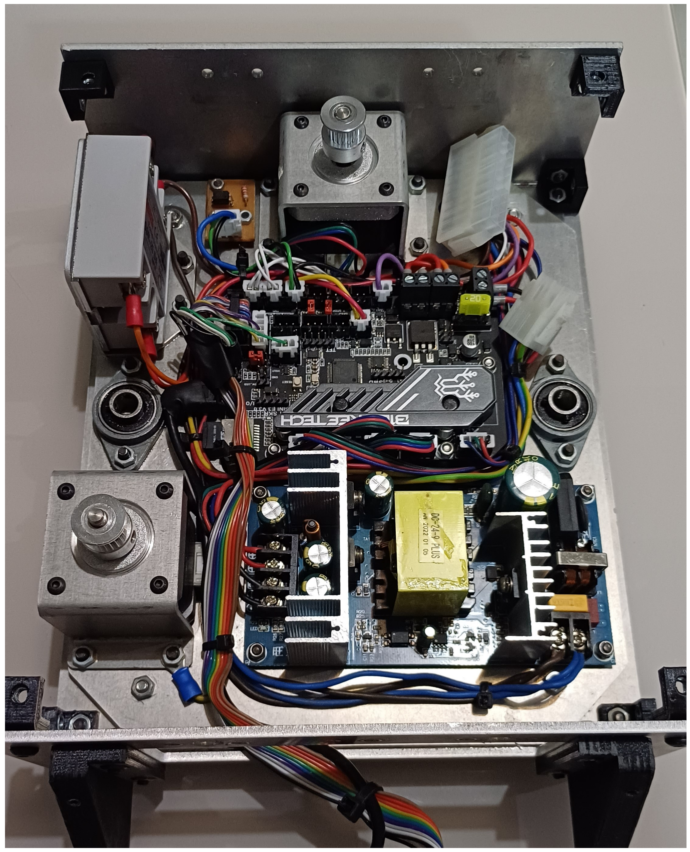


Figure 30: Electronics assembly

Figure 31: Rubber feet

4 Results

At the end of this project, it was possible to comply with all established requirements. The printer has dimensions of 280 x 205 x 320 mm (L x W x H). Its final cost was around R$ 1250.00 (approximately $ 250.00).

It is capable of printing parts in ABS, PLA and PETG, as established. Other materials have not yet been tested. It can print both from the USB port and from the SD card. Thanks to the SKR Mini E3 V3 controller board, it is capable of sensorless homing, eliminating the need for limit switches. Its printing surface is removable and flexible, which makes it very easy to remove the part after printing.

An overall view of the fully assembled Tau 3D printer is shown in Figure 32.

(a) View 1 (b) View 2 (c) View 3

Figure 32: Tau 3D printer

The final quality of the parts is a very subjective parameter, but a part commonly used as a benchmark is the 3DBenchy, a small boat that offers several common challenges in 3D printing, such as curved protrusions, overhangs, text cuts and holes in different orientations. More information about 3DBenchy can be found at: 3dbenchy.com.

The 3DBenchy test part in Figure 33 was printed in PLA, with a printing speed of 30 mm/s and a layer height of 0.15 mm. No support structures were used.

(a) View 1 (b) View 2 (c) View 3

Figure 33: 3D Benchy

Figure 34 shows some other parts printed using the Tau 3D printer. The AAA battery cell is just for scale.

Figure 34: Printed parts